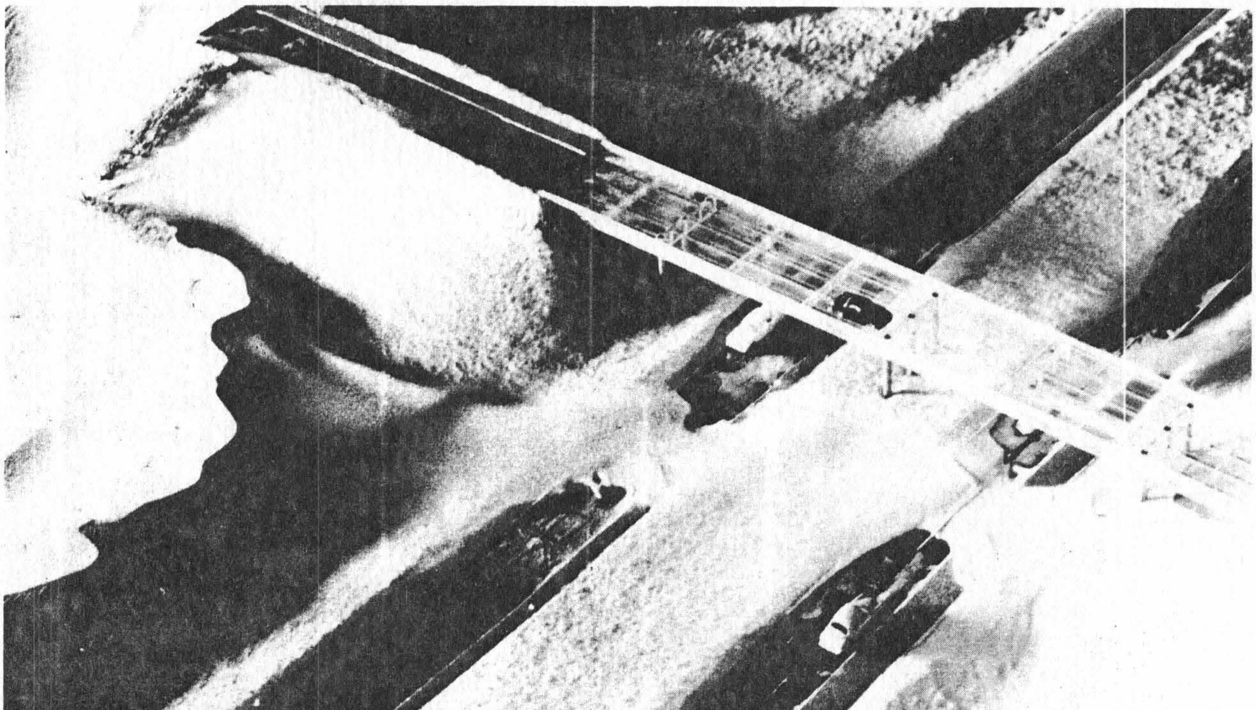
S. L. RING
J. D. IVERSEN
J. B. SINATRA
J. D. BENSON
JUNE 1979

FINAL REPORT

WIND TUNNEL ANALYSIS OF THE EFFECTS OF PLANTING AT HIGHWAY GRADE SEPARATION STRUCTURES



Iowa Highway Research Board
HR-202

ISU-ERI-Ames-79221
Project 1363

In cooperation with the
Highway Division,
Iowa Department of Transportation

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FINAL REPORT

WIND TUNNEL ANALYSIS OF THE EFFECTS OF PLANTINGS AT HIGHWAY GRADE SEPARATION STRUCTURES

Stanley R. Ring
Project Director

Principal Project Staff

James D. Iversen
James B. Sinatra
Jeffrey D. Benson

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DEPARTMENT OF CIVIL ENGINEERING
DEPARTMENT OF AEROSPACE ENGINEERING
DEPARTMENT OF LANDSCAPE ARCHITECTURE
ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY, AMES, IOWA 50011

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NOMENCLATURE

A	Planform drift area or cross section area
A_c	Longitudinal drift cross section area
A_1	Threshold speed coefficient, $u_{*_t} \, (\rho/\rho_p g D_p)^{1/2}$
B	Particle friction Reynolds number, $u_{*_t} D_p/\nu$
C_D	Drag coefficient
D_p	Particle diameter
e	Coefficient of restitution
g	Gravitational acceleration
H	Characteristic vertical dimension (bridge, snow fence, or bush height)
h	All other vertical dimensions
L	Characteristic horizontal dimension (bridge or snowdrift length)
ℓ	All other horizontal dimensions
L^*	Monin-Obhukov stability length
q_s	Mass-transport rate
R	Reynolds number, $U_F D_p/\nu$
t	Time
u	Wind speed
u_*	Surface friction speed
u_{*_t}	Threshold friction speed
U	Reference wind speed (for this study, the speed at bridge height, 0.9 U_∞ for Model 1 and 0.95 U_∞ for Model 2)
U_∞	Wind tunnel free stream speed (above boundary layer)
U_o	Free stream or reference wind speed at initiation of motion (threshold)
U_F	Particle terminal speed

V	Drift volume
W	Vertical wind speed
x	Horizontal distance
z	Height above surface
z_o	Aerodynamic roughness height
z'_o	Aerodynamic roughness height in saltation
λ	Ripple wave length
ν	Kinematic viscosity
ρ	Fluid density
ρ_p	Particle density
τ	Surface shear stress

ACKNOWLEDGMENT

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1. INTRODUCTION

Blowing and drifting snow has been a problem for the highway maintenance engineer virtually since the inception of the automobile. In the early days, highway engineers were limited in their capability to design and construct drift free roadway cross sections, and the driving public tolerated the delays associated with snow storms.

Modern technology, however, has long since provided the design expertise, financial resources, and construction capability for creating relatively snowdrift free highways, and the driver today has come to expect a highway facility that is free of snowdrifts, and if drifts develop they expect highway maintenance crews to open the highway within a short time.

Highway administrators have responded to this charge for better control of snowdrifting. Modern highway designs in general provide an aerodynamic cross section that inhibits the deposition of snow on the roadway insofar as it is economically feasible to do so.

1.1. Defining the Problem

There are situations, even on the most modern highways, where snowdrifting encroaches on the traveled way. These locations may be few in number, but they are a problem for the highway user and the engineers concerned with the design and operation of the highway.

One such snowdrift prone location is at a minor road grade separation structure over a freeway. When the wind is in the same general direction as the minor road embankment, conditions at the grade separation structure may create drifting conditions on the freeway. The snow that is being transported overland by the wind encounters the unique physical features at the embankment and the structure. The resulting local changes in wind speed frequently cause drift formations across the freeway traffic lanes. In some cases, the only snowdrifting that may occur on the roadway will be at these side road overhead structures (see Fig. 1).

Fig. 1. Snow drift at grade separation I-35, mile 184, Iowa.

Traveler safety, the cost of accidents, travel delay, and the added maintenance costs that can accrue are all of concern to the highway agencies. In Iowa the Department of Transportation (DOT) administrators conducted an investigation of the snowdrift problem and contacted the Engineering Research Institute at Iowa State University regarding research on the snowdrifting phenomenon.

1.2. Research Objectives

A considerable amount of research has been done concerning snow transport and snowdrifting phenomena. A number of these research are directly applicable to the design of highways. As a result, highway design criteria and standards reflect these study results. Even the novice highway engineer recognizes that a highway grade should be elevated above the surrounding landscape and have flat slopes in order to increase the likelihood of a snowdrift free roadway. In fact, some state highway agencies have developed sophisticated computer programs with interactive graphics to evaluate the potential for snow deposition.

There are, however, complications in applying snowdrift mathematical modeling concepts to many problem areas. Unusual terrain, adjacent buildings or bands of trees, steep cuts or embankments, vegetation, and bridges, are all examples of unique constraints making it difficult to predict where snow will be deposited. Experiments in the field and observations of snowdrift patterns are time consuming and may be unrewarding.

Experiments with scale models in a wind tunnel were conducted as early as 1934 (Finney 1934a). Modeling experiments can be very useful if valid predictions can be made from the reduced scale models. Conditions can be carefully controlled and many different situations can be simulated in a short period of time with much less expense.

The value of wind tunnel testing to determine snowdrift characteristics has been recognized for many years, but relatively few studies have been conducted. Experiments which have been carried out related to snow fences and highways include those of Becker (1944), Nokkentved (1940), and Finney (1937). Those related to building proximity include Gerdel and Strom (1961), Strom et al. (1962), and in water, Theakston (1970). An experiment related to wildlife shelters was conducted at Iowa State University (see May 1978).

Similar conditions are encountered for modeling drifting sand and dust in air, but even fewer research attempts have been made in this area. An early set of experiments was conducted by Woodruff and Zingg (1952). Most of the recent wind tunnel experiments in this area have been performed at the Iowa State University Wind Tunnel Laboratory and at the NASA Ames Research Center (Iversen et al. 1973, 1975, 1976b; Greeley et al. 1974).

The goals of this research project were two fold: 1) to reproduce the phenomenon of blowing snow with subsequent drifting in the laboratory wind tunnel environment using scale models, and 2) to analyze the effects of strategically placed vegetation, snow fences, or other structures in order to make recommendations for the control of drifting snow at highway grade separations.

The associated objectives were as follows:

1. To design and construct three-dimensional models of an interstate highway grade separation, compatible with wind tunnel requirements.
2. To design test procedures and select appropriate modeling particulate material, and to conduct wind tunnel experiments to reproduce the blowing snow phenomenon and to interpret the results.
3. To introduce various sizes, shapes, and porosities of suitable simulated vegetation and snow barriers, and to analyze their effect on the snowdrifting phenomenon.
4. To make recommendations regarding options to ameliorate the snowdrifting problem at grade separations.

2. REVIEW OF SNOWDRIFTING PHENOMENA LITERATURE AND STATE OF THE ART HIGHWAY DESIGN

2.1. Characteristics of Iowa's Snow Storms

Those persons concerned with maintenance operations on highways should be cognizant of weather characteristics. When do snow storms occur? How much snow can be expected? What direction and at what velocity will the wind blow the snow?

A general knowledge of the state's climatology will aid the maintenance worker or the roadside landscape specialist in analyzing designs and developing control techniques.

In general, Iowa's significant snows appear in December, January, February, and March. In fact, the greatest average monthly snowfall of the year occurs in March (Fig. 2). However, as can be noted from Table 1 occasionally heavy snowfall can occur in each of the other winter months. This type of general information may be an aid in planning, but as any one month or year may be atypical, you can not depend on it.

The wind direction and speed in Iowa has been observed for many years. Table 2 is presented to document these data for the three highest snowfall months--January, February, and March. The percent of time that the wind blows from each point of the compass is tabulated. For January, the wind blows from a direction between due west and due north points 45% of the time. Personal interviews with highway maintenance specialists indicate that winds from the west to north quadrant for north-south highways, and from the northwest to north quadrant for east-west highways create by far the major snowdrift problems. Occasionally a snow storm from the southwest or northeast may also cause a problem.

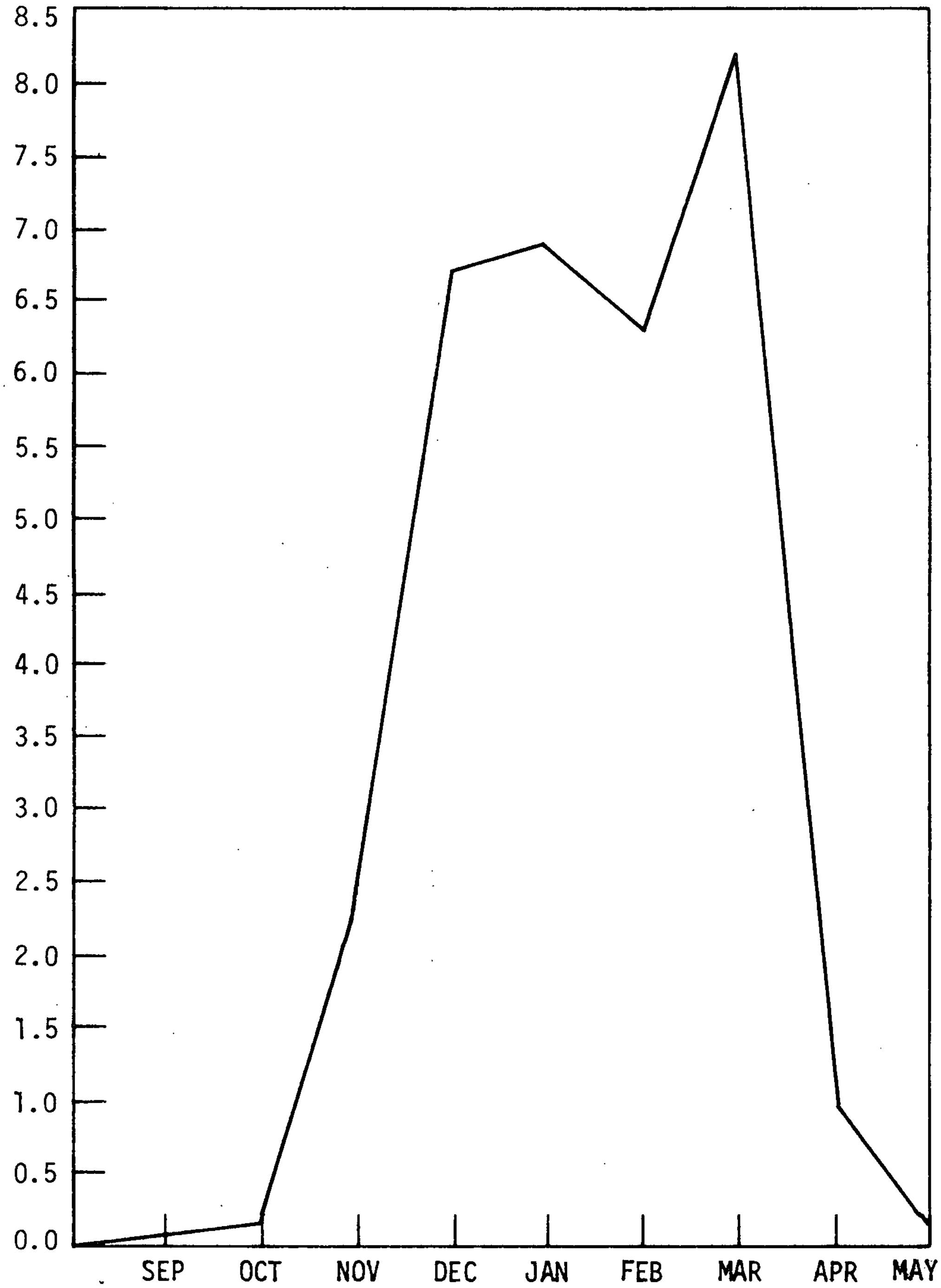

Fig. 2. Normal snowfall for Iowa (1941-1970).

FROM: IOWA DEPARTMENT OF AGRICULTURE STATE CLIMATOLOGIST

Table 1. Iowa's record monthly snowfall (inches).[a]

Rank	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Season
1	4.9 (1925)	8.9 (1959)	17.7 (1961)	20.0 (1979)	22.2 (1962)	23.2 (1951)	9.0 (1973)	1.1 (1947)	59.0 (1961-62)
2	3.6 (1898)	8.7 (1898)	17.4 (1969)	19.4 (1936)	15.9 (1936)	19.1 (1912)	6.0 (1893)	1.0 (1907)	51.7 (1911-12)
3	2.6 (1908)	7.7 (1947)	15.9 (1897)	17.5 (1929)	15.5 (1905)	18.5 (1923)	5.7 (1892)	0.8 (1945)	51.2 (1959-60)
4	2.2 (1917)	7.2 (1934)	13.7 (1909)	14.7 (1930)	14.9 (1939)	17.5 (1965)	4.9 (1928)	0.7 (1911)	50.9 (1935-36)
5	2.0 (1916)	6.9 (1928)	12.9 (1902)	13.6 (1932)	12.5 (1929)	16.2 (1959)	4.5 (1896)	0.6 (1917)	49.1 (1974-75)
6	1.7 (1923)	6.8 (1909)	12.8 (1951)	13.1 (1975)	12.3 (1960)	15.9 (1960)	4.4 (1975)	0.6 (1938)	46.1 (1950-61)
7	1.6 (1905)	6.6 (1971)	12.6 (1911)	12.8 (1947)	11.6 (1975)	15.2 (1952)	4.3 (1945)	0.3 (1935)	44.7 (1904-05)
8	1.5 (1937)	6.4 (1957)	12.3 (1904)	12.7 (1949)	11.6 (1945)	14.3 (1961)	3.9 (1936)	0.3 (1944)	43.9 (1928-29)
9	1.4 (1967)	6.3 (1919)	11.7 (1968)	12.6 (1898)	11.5 (1950)	13.9 (1948)	3.8 (1917)	0.1 (1967)	43.6 (1964-65)
10	1.2 (1913)	5.8 (1974)	11.1 (1977)	12.6 (1910)	11.3 (1978)	12.6 (1901)	3.7 (1938)	0.1 (1966)	43.2 (1951-52)
Normal (1931-1960 Average)	0.1	3.1	5.9	7.6	6.4	8.0	1.2	0.1	32.4

[a]Source: Paul J. Waite, State Climatologist, March 1979.

Table 2. Percentage frequencies of wind direction and speed.

January

DIRECTION	HOURLY OBSERVATIONS OF WIND SPEED (IN MILES PER HOUR) 8-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 OVER	TOTAL	AV. SPEED
N	.1	1.1	2.7	3.0	1.2	.3	.1			8.4	12.4
NNE	.1	1.0	1.8	1.9	.6	.1	+			5.4	12.5
NE	.2	.9	1.6	1.4	.3	+				4.4	11.4
ENE	.1	1.0	.8	.3						2.3	8.0
E	.2	1.3	1.0	.3	+					2.8	8.1
ESE	.1	1.0	1.9	.8	.1					3.9	9.7
SE	.2	1.5	3.6	1.6	.1					7.0	10.0
SSE	.2	1.4	2.6	1.9	.1	+				6.2	10.5
S	.1	1.4	3.2	2.3	.2	+				7.3	11.1
SSW	.1	.7	1.6	1.5	.6	.1				4.5	12.5
SW	.2	1.1	2.3	1.3	.3	.1	+			5.4	11.1
WSW	.1	1.0	1.9	1.1	.2	+				4.3	10.5
W	.2	1.4	1.8	1.2	.4	.2	+			5.2	11.4
WNW	.1	1.3	2.7	2.6	1.1	.7	.2	+		8.7	14.3
NW	.1	1.2	3.2	4.4	2.9	.8	.1			12.7	15.3
NNW	.1	1.0	2.5	3.6	2.3	.7	.1			10.3	15.3
CALM	1.3									1.3	
TOTAL	3.4	18.2	35.3	29.1	10.4	3.1	.5	+		100	12.1

February

DIRECTION	HOURLY OBSERVATIONS OF WIND SPEED (IN MILES PER HOUR) 8-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	47 OVER	TOTAL	AV. SPEED
N	.1	.7	1.9	2.9	1.2	.3	+			7.1	14.4
NNE	.1	.7	1.8	2.8	1.2	.3	+			6.9	14.4
NE	.1	.7	2.0	1.5	.1	.1				4.5	11.3
ENE	+	.7	1.5	1.0	.2	.1				3.5	11.6
E	.1	.8	1.6	1.2	.3					3.9	11.6
ESE	+	.8	2.7	1.6	.4	+				5.4	11.6
SE	.1	1.1	3.1	1.7	.1					6.1	10.7
SSE	.1	.9	2.1	1.2	.2					4.6	10.7
S	.1	.7	2.4	1.8	.4					5.4	11.8
SSW	.1	.7	2.3	1.9	.4	+				5.4	11.8
SW	.1	1.0	2.1	1.1	.5	.2	.1	+		5.1	12.3
WSW	.1	1.0	1.8	1.1	.5	.1	+	+		4.7	12.1
W	.1	1.3	2.0	1.2	.4	.1	.1			5.3	11.7
WNW	.1	1.3	3.0	3.3	1.7	.5	.1			9.9	14.4
NW	.1	1.3	3.4	4.3	2.1	.8	.2			12.2	14.9
NNW	.2	.7	2.6	2.9	1.6	.3	.2	+		8.5	14.5
CALM	1.3									1.3	
TOTAL	2.1	14.3	36.2	31.3	11.3	2.9	.9	.1		100	12.7

March

DIRECTION	HOURLY OBSERVATIONS OF WIND SPEED (IN MILES PER HOUR) 8-3	4-7	8-3	13-18	19-24	25-31	32-38	39-46	47 OVER	TOTAL	AV. SPEED
N	.1	.5	1.7	2.9	2.2	.8	.1			8.4	16.4
NNE	.1	.5	1.5	2.5	1.0	.3	+			6.0	14.6
NE	.2	.7	1.7	1.8	.7	.1				5.2	12.8
ENE	.1	.9	2.0	1.9	.7	.1				5.6	12.5
E	+	1.3	2.3	2.0	.4	.2				6.2	12.0
ESE	.1	1.2	3.5	2.4	.5	.2	.1			8.1	12.4
SE	.1	1.1	3.0	2.4	.5	.1				7.2	11.9
SSE	.1	.8	2.3	2.0	.3	.1				5.5	12.0
S	.2	.8	1.8	2.0	.6	.1	.1			5.5	12.8
SSW	+	.4	1.3	1.5	.5	.1		+		3.8	13.8
SW	.1	.5	.7	1.1	.3	+	+	+		2.7	13.0
WSW	.1	.6	.9	.9	.5	.2	+			3.2	13.8
W	.1	.9	1.5	1.3	.5	.4	.1			4.9	13.7
WNW	.1	.8	2.2	2.8	1.4	1.2	.6	.1		9.2	17.0
NW	.1	.8	1.9	3.6	2.4	1.3	.1			10.2	16.9
NNW	.1	.7	1.2	2.5	2.0	.6	.2	+		7.2	16.7
CALM	1.1									1.1	
TOTAL	2.5	12.6	29.4	33.6	14.7	5.7	1.4	.1		100	14.1

In order to graphically illustrate these tabular data a wind rose has been plotted (Fig. 3). The percent of time, by direction, that the wind blows at certain speed ranges has been plotted. The importance of design considerations for winds from the NW and NNW points are apparent.

The average seasonal snowfall accumulation in Iowa ranges from 40 inches in northeast Iowa to 25 inches in southeast Iowa (Fig. 4). Also, the average number of days with snow cover accumulations of one inch or more ranges from 90 days in northern Iowa to 40 days in southern Iowa (Fig. 5). The intensity of maintenance operations may reflect this average snowfall range, but the need to reduce snowdrifting problems from any one storm exists across the state.

In order to design for snowdrift control the designer should have an understanding of certain aspects of the natural forces and the physical features at the location. The anticipated direction, speed, and volume of snow transported should be known. Generally, those maintenance specialists who have dealt with the problem for years have developed an intuitive judgment capability. They know from experience.

The effects of groves of trees, clumps of bushes, building clusters, sharp terrain changes, changes in upwind surface roughness and vegetation, and other physical features can have a very significant effect on snow-drifting, and are not as readily understood. A very few specialists have developed an understanding of the phenomenon, and may be able to predict snowdrift patterns--especially in uncomplicated conditions. Figure 6 illustrates upwind development that will have a significant effect on the potential to predict snow drifting downwind from the buildings.

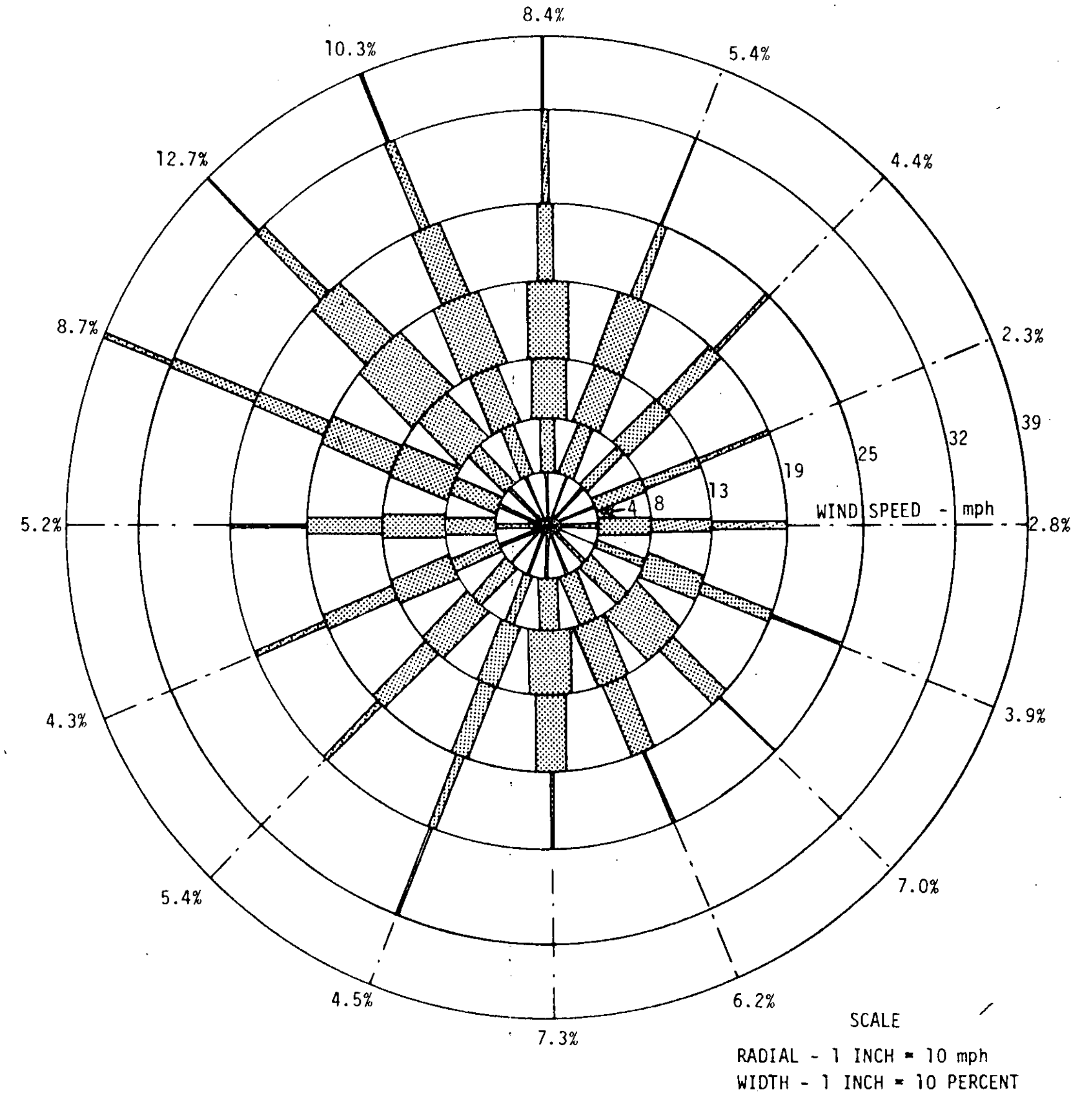

Fig. 3. Percentage frequencies of wind direction and speed for month of January.

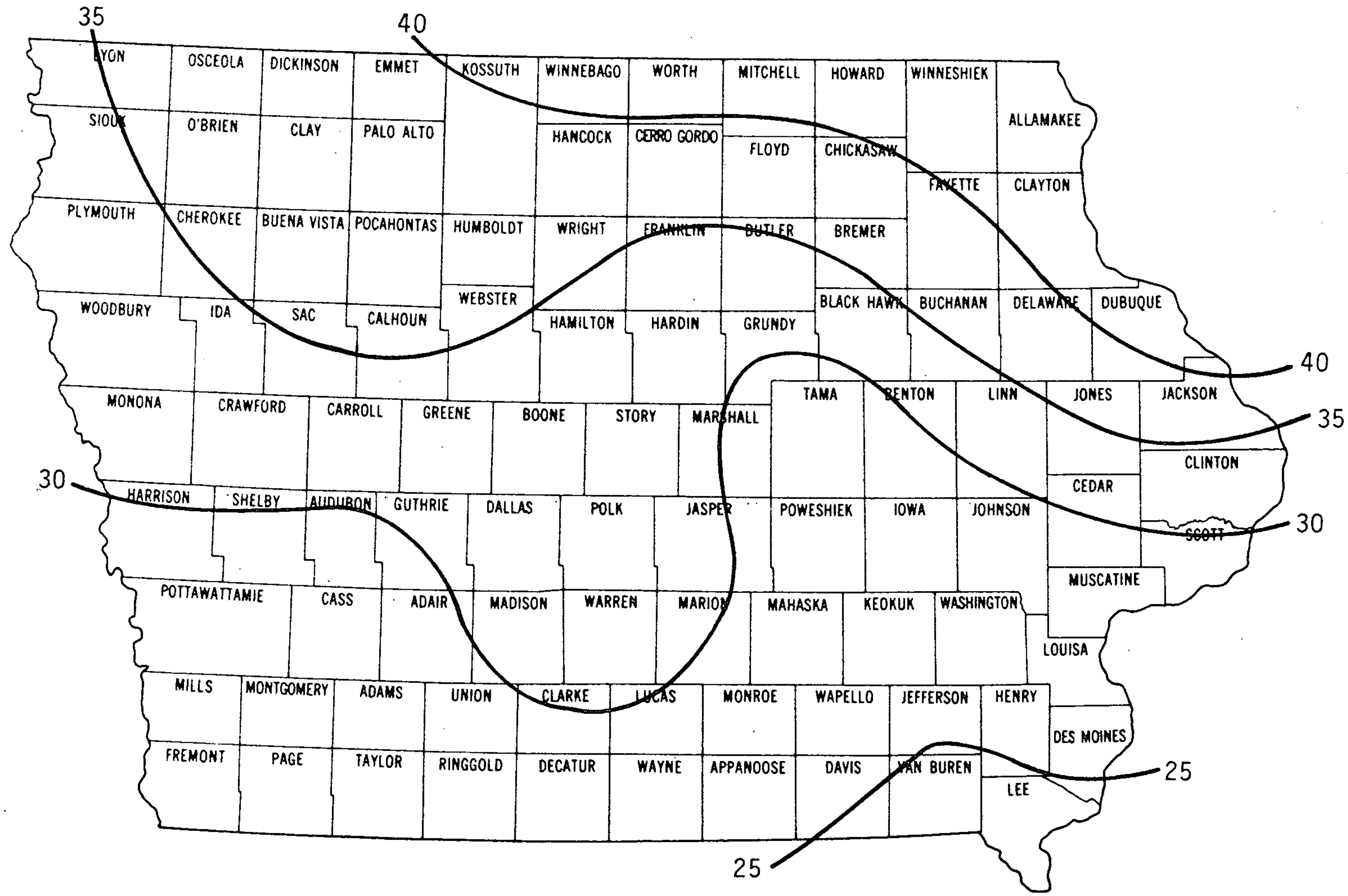

Fig. 4. Average seasonal snowfall (inches).

FROM: IOWA DEPARTMENT OF AGRICULTURE STATE CLIMATOLOGIST

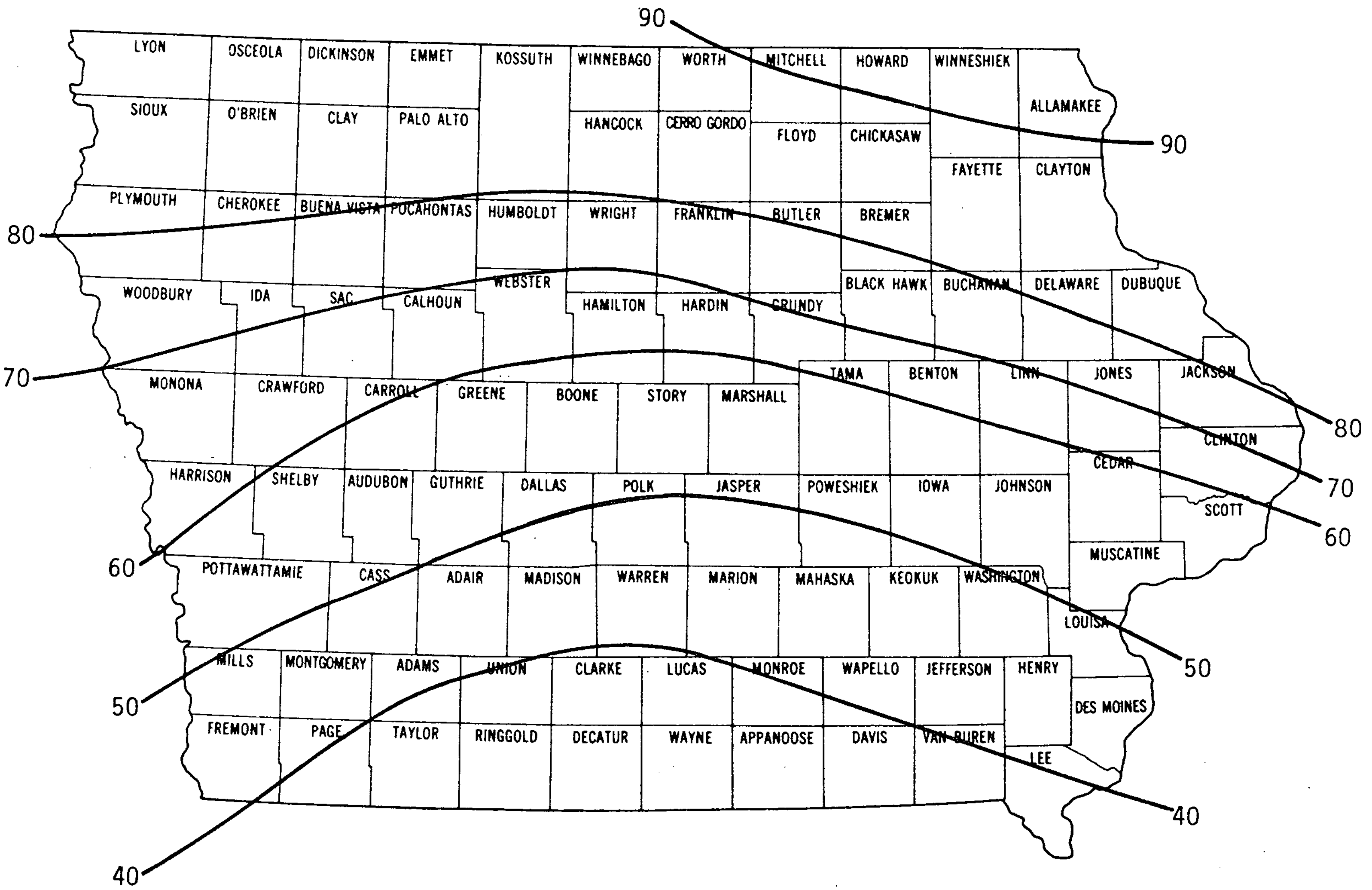

Fig. 5. Average annual days with snow cover one inch or more.

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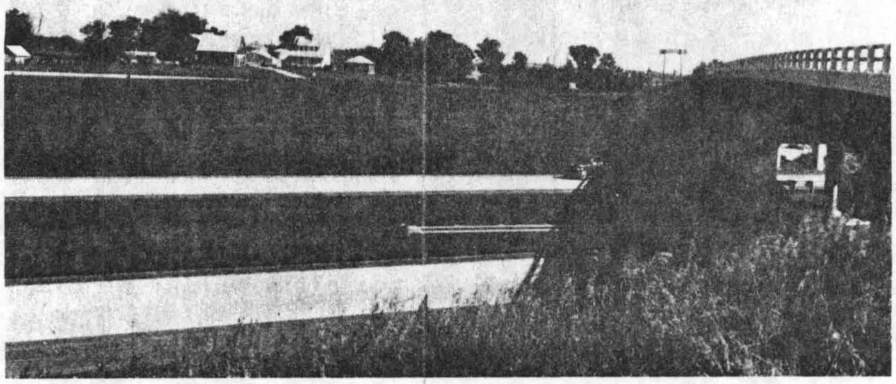

Fig. 6. Illustration of upwind development that will have an effect on snow drifting.

A few researchers have developed dependable prediction capabilities and in many cases have published their results. These empirical and theoretical models of snowdrifting phenomenon must be interrelated with climatology for the ultimate purpose of controlling snowdrifts. A knowledge of these principles should be an important tool for those highway specialists working in the area of snowdrift control.

2.2. Basic Highway Design Practices to Minimize Snow Deposition

Highway engineers have long recognized the relationship between roadway design and the propensity for snowdrifting on a highway. Radzikowski (1938) noted that snow accumulation was a problem to the road user, and also created potential moisture and structural problems. He suggested an emphasis on snow sheds, tree plantings, snow fences, and the design of the highway itself to prevent the snow from collecting on the highway.

Finney (1934a,b, 1937, 1939), commencing with a graduate thesis at Iowa State College in 1934, published the results of numerous studies concerning snowdrift control through the design of the highway. He noted (1939) that snowdrift control on the highways may be classified under artificial barriers, natural barriers, highway design, and highway betterment. Artificial barriers involve snow fence design, and natural barriers involve plantings. The application of snow transport principles are used in the original design of the highway, and highway betterment involves spot type improvements to eliminate snowdrift problems.

Finney's (1939) Bulletin No. 86 is a classic work in the field of highway design for snowdrift control. In recent years, Tabler's work (1973, 1974, 1975a, 1978a, 1978b, 1979) can also be considered classic, especially in snow fence design.

Finney noted in a 1939 survey of snowdrift control by highway design practices, that 12 states extensively considered the snowdrift factor. Seven others considered it in a limited way.

Finney noted that snowdrifting on the highways generally could be attributed to one of the following:

- Right-of-way fences
- Right-of-way vegetation and debris
- Design of the highway grade, cross section, and alignment, the adjacent topography, and highway appurtenances

- Non right-of-way structures such as billboards or buildings
- Drifting created by snow removal methods.

He also noted that the majority of these conditions could be eliminated by corrective measures. In some cases, however, concern for economy overrules the corrective measures prepared and the removal of snowdrifts remains a problem. Finney noted the need for a snowdrift study as a part of the highway location and design process.

A very important contribution by Finney (1934a) related to air flow studies of the highway cross section in a small wind tunnel. A mixture of flake mica and balsa sawdust simulated snow. The purpose of the study was to identify the characteristics of eddy areas that cause drifts to develop, and to analyze the highway cross section in terms of snowdrifting. Finney did not consider either the principles of similitude in his experiments or the characteristics of the atmospheric boundary layers. Thus, the results, while qualitatively approximately correct, contain some quantity errors.

Finney determined that the limit of the eddy area (e.g., the leeward end of snowdrift accumulation) would always be at a horizontal distance of 6.5 H (over heights of two to ten feet). (H is the height of the obstruction, or in this case the depth of the cut.) See Fig. 7.

This characteristic for predicting snowdrift length (versus height) was a powerful tool. Since these tests in the 1930s it has been shown that a solid barrier, which functions similarly to a cut section, probably will generate drift areas in the range of 7-10 H. A designer may thus widen the ditch, as the cut depth increases, in order to ensure that the end of the 7-10 H eddy limits does not fall on the roadway.

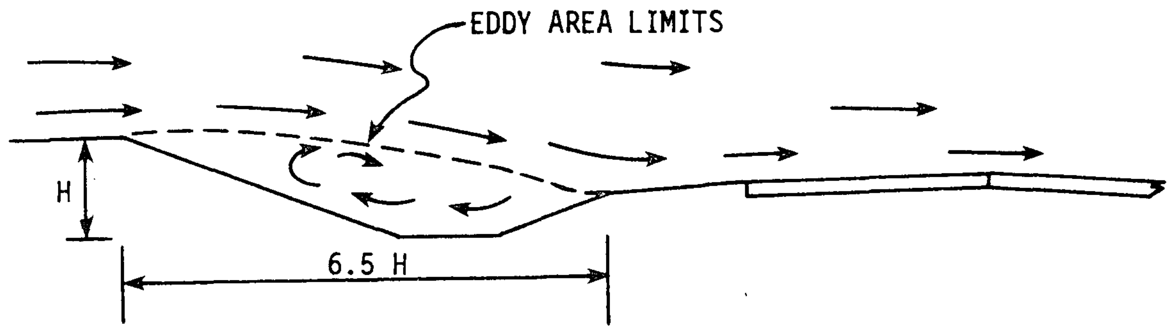

Fig. 7. Drift forming eddy in a highway cut (Finney 1934a).

Finney's wind tunnel tests clearly illustrated the benefits of flat slopes and rounding. Figure 8 illustrates the effect of changing the backslope ratio to achieve a wind swept snow free section. Figure 9 illustrates the benefits of rounding the top and bottom of slopes.

Figure 10, from Finney's early wind tunnel work, illustrates the benefits to be derived from flat foreslopes. As most highway designers and maintenance personnel know, a 6:1 foreslope freeway cross section elevated a few feet above the surrounding terrain does not have a snow drift accumulation problem unless other factors in the environment enter the picture. Figure 11 illustrates a flat foreslope with rounding on a two-lane roadway and Fig. 12 illustrates the same cross section under snow blowing conditions.

In summary, Finney made the following recommendations in his 1939 publication. These admonitions still hold true today.

1. Raise the grade line above the adjacent ground equal to the average depth of snow.
2. Avoid cut sections through alignment and profile design. Shallow cut sections (less than six feet) are troublesome.

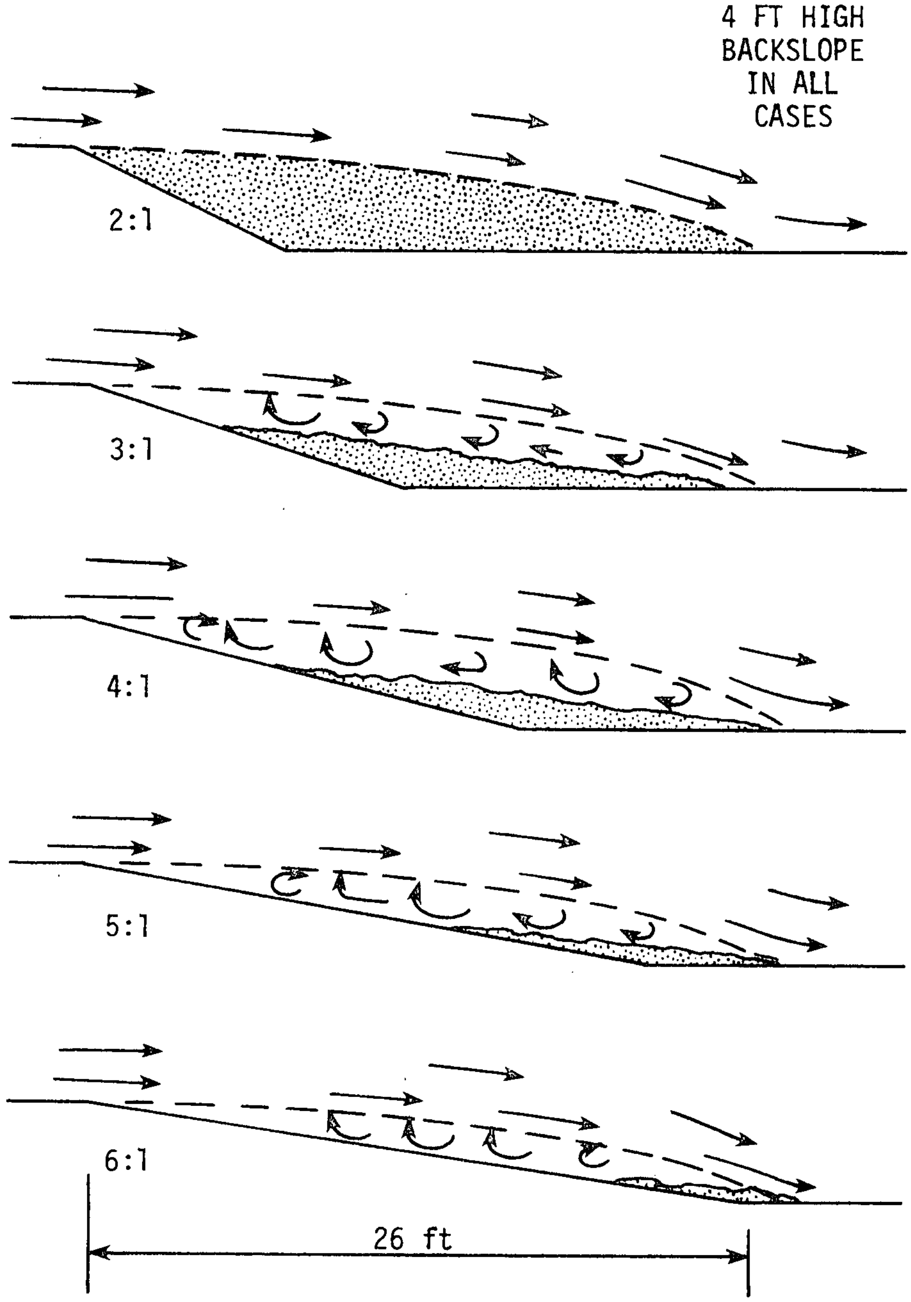

Fig. 8. Effect of variations in backslope on snowdrift accumulation (Finney 1934a).

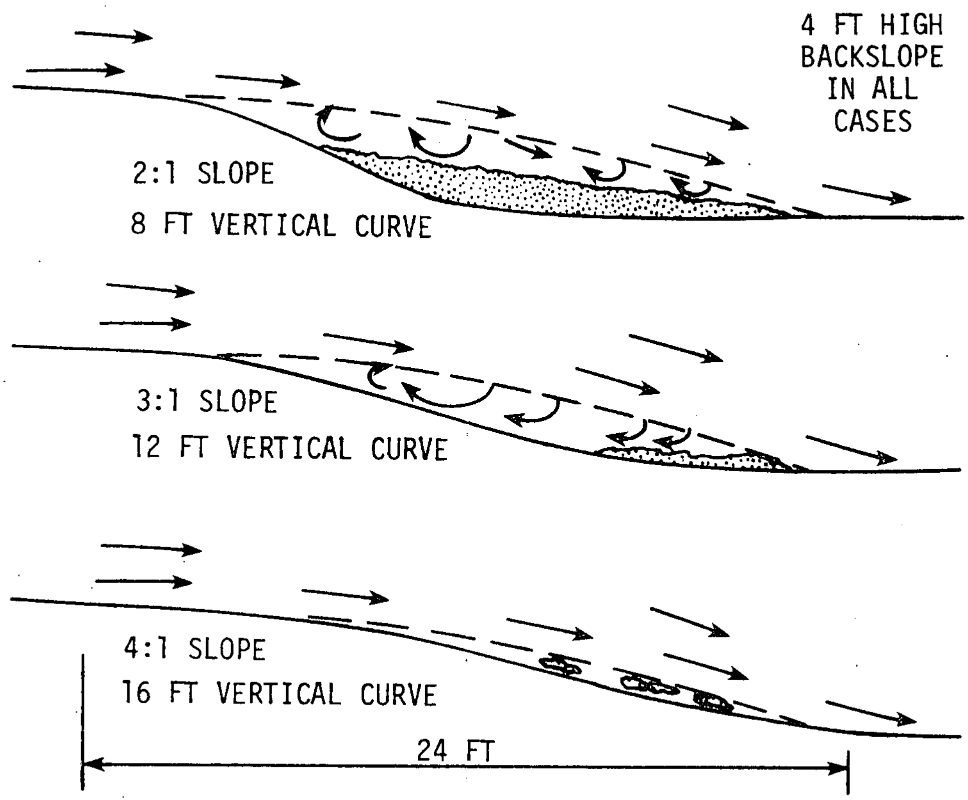

Fig. 9. Effect of rounding top and bottom of slope (Finney 1934a).

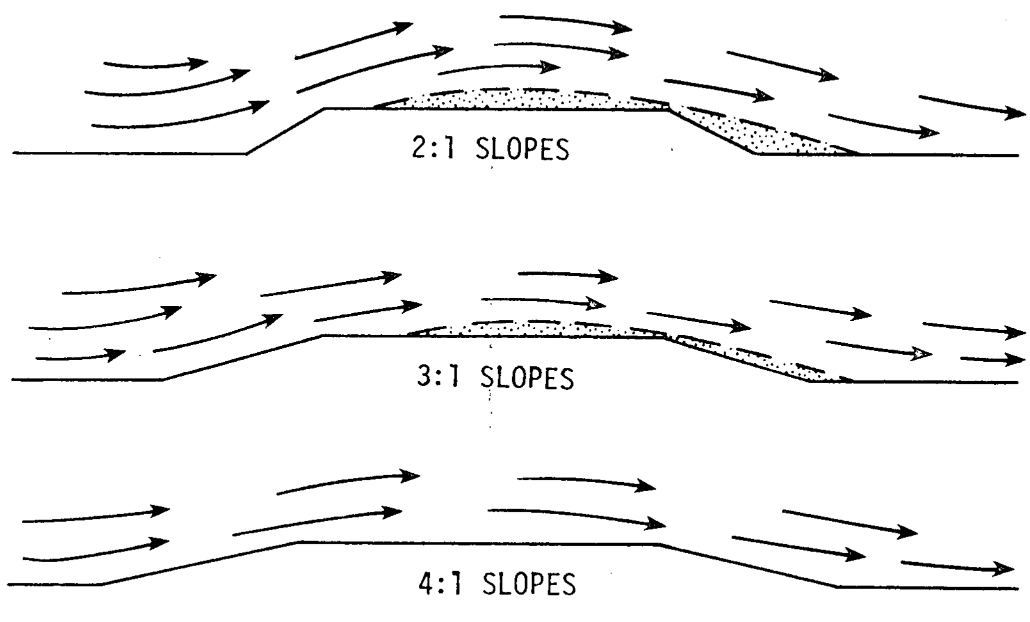

Fig. 10. Effect of foreslopes on air flow across roadways (Finney 1934a).

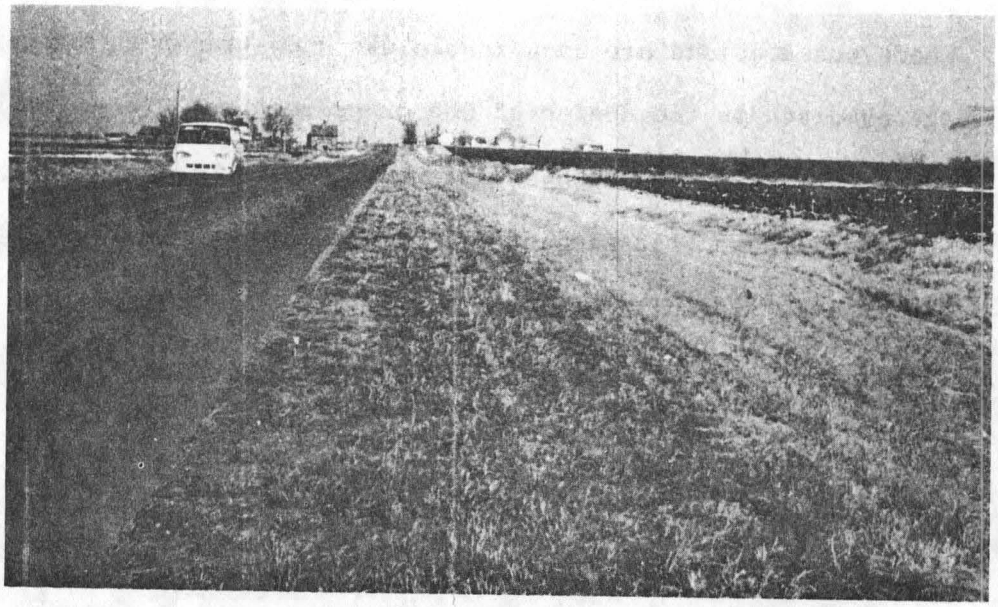

Fig. 11. Typical two-lane rural Iowa roadway with flat foreslopes.

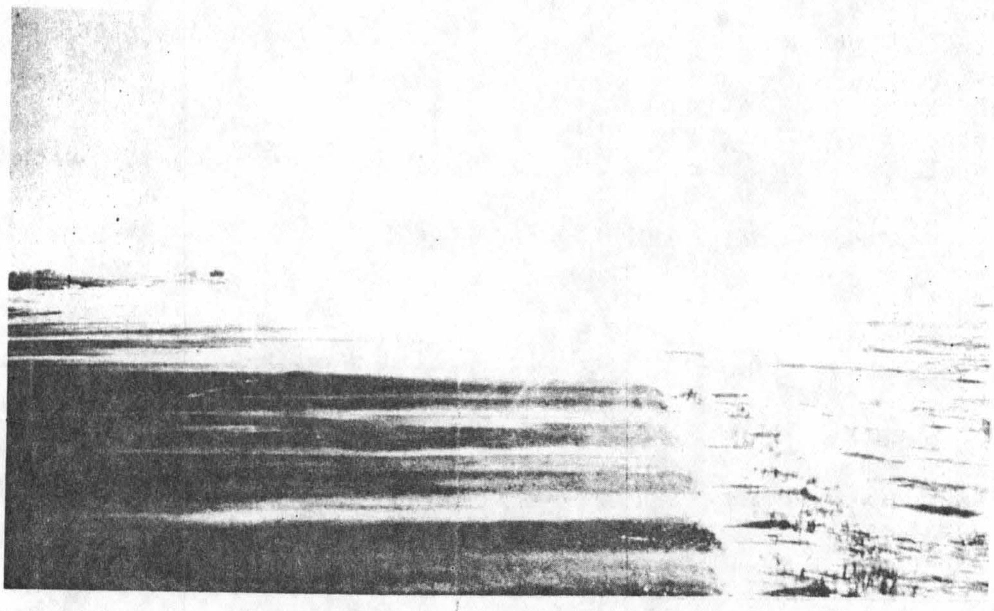

Fig. 12. Smooth cross section and flat foreslopes provide snow free roadways.

3. Where cut sections are unavoidable use snow transport and storage concepts in the design of the cross section. (e.g., wider ditches, flatter backslopes, and rounded slope intersections.)
4. In general, use flat slopes (4:1 or greater), wide shoulders, and shallow wide ditches.
5. Eliminate guardrail if possible and other appurtenances such as curbs.
6. Utilize a knowledge of snow transport phenomenon in highway location.

Cron (1967) called attention to the problems of prevailing wind information, and topographic conditions in highway location and design. He also noted that appurtenances, such as curbs, guardrail, signs and fences could create problems.

Mellor (1970) provides a brief review of the blowing snow phenomenon. Practical procedures for controlling deposition of wind blown snow are reviewed.

The literature is replete with articles on blowing snow phenomenon and the control of drifting through highway design, strategic plantings, and snow fence applications. Most, however, did not offer significant contributions over Finney's work--until Tabler's work in recent years.

Tabler has made significant contributions to the state-of-the-art in highway design to reduce snowdrifting problems on the roadway. One of his more recent reports, "Predicting Profiles of Snowdrifts, in Topographic Catchments" (1975) is representative of the value of his work.

Through multiple linear regression, Tabler determined that snow slopes could be predicted when an equilibrium profile of a snowdrift had been established. In a comparison to Finney's 1939 work, Tabler noted that drift length varied exponentially with height, but did converge at 6.5 H for embankments of great height. See Fig. 13.

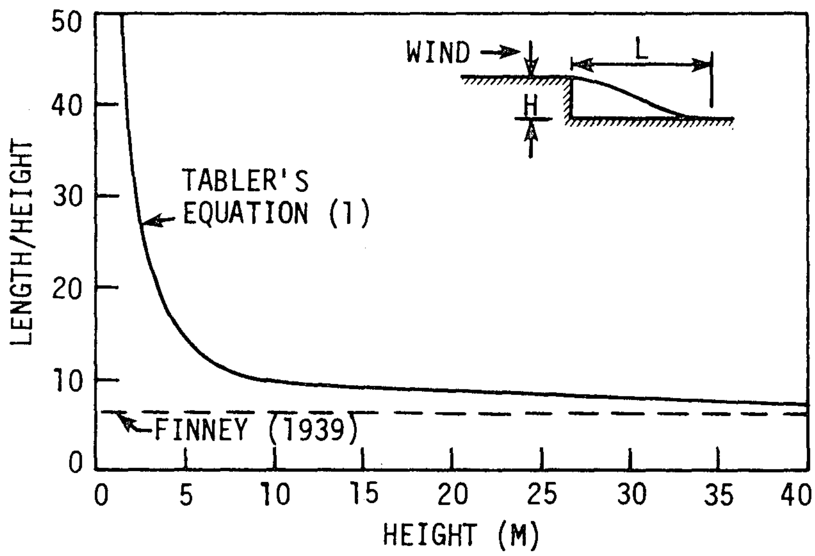

Fig. 13. Relationship between height (H) of vertical embankment and drift length (L/H), comparing results from Tabler's Eq. (1) with those of Finney (1939). Adapted from Tabler (1975).

Tabler also verified Finney's finding that there is no accumulation on a downwind snowdrift slope of 1:6 (about -17%).

These results can be applied directly to the field of highway cross section design. The Wyoming Highway Department uses computer programs to redesign locations of snowdrift encroachments.

Figure 14 is an example of the use of an interactive graphic computer design, to eliminate snowdrift accumulation simply through adjusting cross sections.

In addition to the literature search, a number of interviews were conducted with Iowa Department of Transportation Maintenance Supervisors.

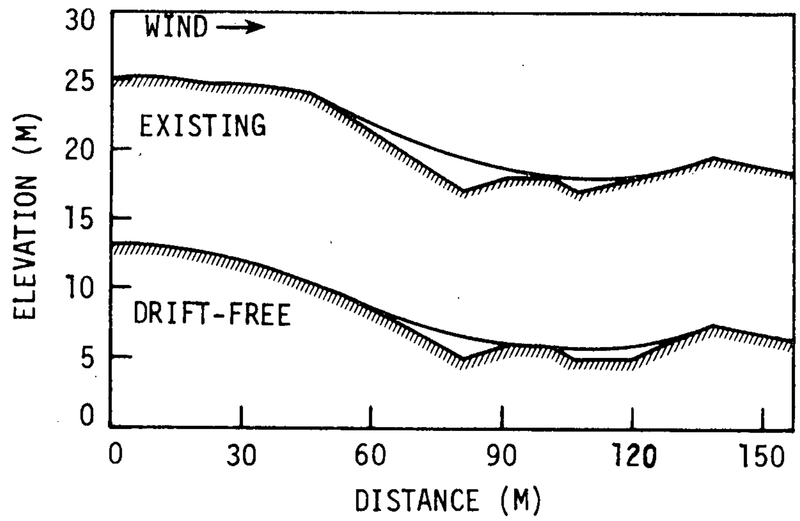

Fig. 14. Predicted snow accumulation before and after redesign. East-bound lane off-ramp, Walcott Junction, I-80 (Wyoming). Adapted from Tabler (1975).

Those with responsibilities on I-35 from Des Moines north to Minnesota were interviewed primarily to discuss their interpretation of the problem.

As a part of this research effort a survey of adjacent state highway organizations was conducted. The purpose of this survey was to obtain information regarding highway design considerations to minimize snow deposition problems. A copy of the survey instrument and a summary of the results are included in the Appendix (sections 7.3. and 7.4.).

The following comments summarize these data:

- Seven states specifically noted that they have a policy of widening the ditches in locations where snow deposition may occur.
- One state added that at deep vertical cuts a large amount of snow is stored in the vertical face of the snow bank at the back slope.
- Five states emphasized that flat foreslopes allowed the blowing snow to sweep across the roadway with little deposition.

- Two states commented that the problem areas are in a 2 ft to 5 ft cut section (below the adjacent land). This is especially true in narrow right-of-ways.
- Two states emphasized the value of rounding at the point where foreslope meets shoulder and backslope meets adjacent land.
- The elimination of guardrail was noted as a benefit.
- Designing a grade line above the adjacent terrain was emphasized by most states. The desirable grade elevation ranged from 1.5 ft to 4 ft.
- One state noted that the right-of-way area was mowed in the fall to maintain a wind swept free cross section.
- In general, plantings were not used to control snowdrifting except at specific locations. One state noted that plantings may be a problem, and one state has discontinued plantings in the right-of-way. One state has a very intensive planting program.
- Many states noted the problems of W beam guardrail and were redesigning to minimize its use.
- A majority of states interviewed used two span over-crossing bridges to eliminate the right hand piers.
- Problems at grade separation structures exist in a number of states.

Many survey responses included extensive references on the subject of snowdrifting. A number of states have developed a specific design procedure manual of operations for considering the snowdrifting problem. Wyoming is in the process of expanding their design guides based on Tabler's studies.

In summary, it can be stated that a considerable bank of knowledge exists regarding the phenomenon of snow transport and snowdrifting. The works of Finney and Tabler are especially applicable to highway design and operations, and should be utilized by persons involved in these activities. The newly evolving computer applications for cross section design should be introduced in every design office in the highway snow belt.

It is not apparent from a search of the literature that the unique problems at over-crossing grade separation structures has been addressed-either theoretically or empirically. In most cases, the combination of topography, trees, buildings, adjacent field crops, cross section and guardrail present so many variables that only a few experts would be able to predict the shape of snowdrifts and their locations.

Long term field testing under controlled research conditions or laboratory modeling are needed to develop knowledge in this area.

2.3. The Effects of Vegetation on Snow Deposition

The relationships between plants and wind that create shelter and snowdrifting are so basic that undoubtedly man has been putting plants to use for protection for many centuries. Systematic investigations into these relationships were started only at the beginning of this century. Some of the earliest observations on snowdrifting associated with plants were made by Vaughn Cornish in his 1902 report on snow transport in general. Experimentation and field measurement on shelter caused by plants were first reported on in the United States by Bates

(1911) and in Denmark by Nokkentved (1938). Investigations in the United States, Russia, Japan, Great Britain, Denmark and Germany have led to reports which detail the value of plants as windbreaks to agriculture, forestry, architecture, and highway design. Some of the early work on using plants for snow control on highways was done by Burton (1925) and especially Finney (1934, 1937). Much research on the subject of windbreaks occurred in the late 1940s and 1950s: in the United States by Woodruff and Zingg (1953), Woodruff (1954), Woodruff et al. (1963) Stoeckler (1962), Chepil (1949), and Stoeckler and Dortignac (1941) among others; in Russia by Golubeva (1941), Konstantinov (1950), Yadin (1950) and many more; in Japan by Sato et al. (1952) and Iizuka (1952); in Germany by Naegeli (1941, 1946, 1953) and Blenk and Trienes (1956); and particularly in Denmark where Jensen (1954), continuing with Irminger's and Nokkentved's research, published his book, Shelter Effect. This book is a review of knowledge on the basics of shelter as it was understood at that time. A later report by Van Eimern (1964) presented the state of the art knowledge on the basic plant characteristics and how they could affect wind.

From these many investigations it is known that height, width, porosity, and arrangement of plants within a plant mass are the chief factors influencing snowdrifting. How these physical properties of plants affect snowdrifting is also a result of surrounding conditions such as terrain, upwind ground cover, orientation of the planting, and windspeed. Recent experimentation has concentrated on these individual characteristics, particularly on porosity of plants (Rayner 1962; Plate 1970; Hagen and Skidmore 1971a,b; Burgy 1961; and Seginer 1971).

This section will discuss what these researchers have discovered over the years about the basic relationships between a plant's physical properties and its surroundings that may create snowdrifting. The extent to which it is possible to manipulate these factors to create the appropriate snow control for particular situations will also be discussed.

2.3.1. Relationship of Wind Velocity Reduction and Snowdrifting

As will be discussed later in this report, snowdrifting occurs when wind of a sufficient velocity to pick up snow (the threshold velocity or more) passes over a snow covered area and then encounters an obstruction. The obstruction diverts the wind and the result can be a separated flow region behind, or leeward of the obstruction. The wind velocity in this region is much less than upwind of the obstruction (the open field velocity) and consequently snow is deposited in the separated flow region. Often times there is a region of reduced windspeed in front (or windward) of the obstruction where snow is also deposited. As pointed out earlier, there are many factors that determine the amount and extent of these velocity reductions, but there is a definite interconnection between velocity reductions near obstructions and snowdrifting. Because there has been more data collected on wind reductions behind various kinds of plant windbreaks than actual snowdrift measurements, much can be added to our knowledge of snowdrifting if some time is spent in understanding the relationship between zones of wind reduction near plant windbreaks and snowdrifting.

Some wind velocity reduction will always occur at least in a portion of the space leeward of a plant mass. In some cases, with very thick or impermeable plant masses, there is a turbulent separated flow zone leeward. In this zone the wind velocities are much lower than the open field velocities. Further downwind the turbulence may decrease in intensity, but there is still a wind velocity reduction. A review of some experiments indicates that snowdrifting does not occur within the entire zone of wind velocity reduction. In wind tunnel tests of a solid wall Woodruff (1954) found a 25% reduction in open field velocity at a distance leeward of 21.5 times the height of the wall (21.5 H). Measurements of actual snowdrifts associated with solid walls by Tabler (1978b) indicate they extend only to about 10 H leeward. Finney's (1934a) wind tunnel studies also indicated a leeward drift. Similarly, for a solid fence of 14 H length, Naegeli (1946) found a slight reduction in open field wind velocity as far as 30 H leeward of a dense plant windbreak, while Mastinskaja (1953) reports a snowdrift length of only 80 m leeward of a tall, dense plant windbreak. George et al. (1963) found that drifts leeward of dense plant windbreaks commonly extend only to 10 H. These same researchers found that the wind velocity at 20 H leeward of a single row of cottonwoods was 83% of the open field velocity. Frank et al. (1975)--in measuring snowdrifts behind a single row of Siberian Elms, a species with a similarly open form as the cottonwoods--found the drift extends only to a maximum of 15 H.

If, as has been consistently reported, the snowdrift leeward of a plant windbreak does not reach all the way to the end of the zone of wind velocity reduction, then what is the relationship between wind reduction and snowdrifting? In attempting to answer this question, E. A. Finney (1934, 1937) stated that the snowdrift length behind a porous barrier will be equal to the length of the eddy area (at least at lower wind velocities). He went on to say that the length of this eddy area expressed in terms of barrier heights changes for different porosities of barriers, although the average length is 15 H. Finney qualified this statement by saying that the snowdrift length behind a solid fence does not extend to the end of the eddy area. Later researchers have shown that snowdrifts can form behind plant windbreaks with few or no lower branches (Stoeckler and Dortignac, 1941; Frank et al. 1975). In this situation there is sufficient wind passing underneath the barrier to virtually eliminate the eddy area, yet there is still a velocity reduction and snowdrifting. A more complex relationship between wind velocity reduction and snowdrift configuration exists than that originally proposed by Finney.

The importance of examining wind velocity reduction to help in understanding snowdrifting becomes evident when looking at the influence of changes in the physical properties of the barrier or its surroundings. An example of the influence of such a change was given by Tabler (1978b) when he noted that for a solid fence the snowdrift length will reach about 10 H, while it will be more on the order of 27 H for a 50% porous fence. It has also been noted that the point of maximum depth moves further leeward as the barrier porosity increases (Frank et al. 1976; Naegeli 1953). Similarly, the point of maximum wind reduction for a solid barrier is very close to the barrier, but this moves out to 3 H to 5 H for a porous barrier (Gloyne 1954). It is this type of information about how different barriers perform, as shown by changes in wind reduction patterns, that can be useful in understanding how particular windbreak properties may affect snowdrifting. This sort of comparative examination will be used in analyzing wind reduction effects of windbreaks in this section, and will shed some light on the data provided on snowdrifting itself.

2.3.2. Plant Mass Characteristics Affecting Snowdrifting

Individual plants are of little importance in creating shelter, and although they do cause changes in wind patterns sufficient to form snow deposition areas, the small size and unpredictability of the deposition pattern make isolated plants insignificant for snow control. When planted together in large enough groups, called plant masses, the potential for snow control becomes apparent. This is true for all types of plants, trees, shrubs, grasses, and even agricultural crops. It is the physical characteristics of plant masses taken as a whole that determine snowdrift length and volume.

The most commonly used and best researched type of plant mass (windbreaks) for snow control is a combination of trees and shrubs. Grasses and crops (discussed later) can also be used for snow control, as well as other plant combinations other than windbreaks. It has been almost universally understood since the earliest research (Bates 1911) that height and porosity are the most important physical characteristics of a plant mass that determine snowdrift configuration. When Jensen wrote his book on shelter effect that summarized research conducted up to that point, he gave a formula to determine drift length: $L = (36 + 5h)/K$ (Jensen 1954), where h is the height of the barrier and K is a function of screen density. While it now seems that this formula is too simple to predict actual snowdrift measurements in the field, it does reflect the importance placed on height and porosity.

It is now known that the overall lateral length of the plant mass is important. In order for the leeward zone of influence, or zone of wind velocity reduction, to reach the maximum length possible for a given height and porosity, the length of the windbreak must be at least 30 times its height (Tabler 1978b; Read 1964). Otherwise, the effect of wind coming around the end of the plant mass shortens what would be the maximum extent of protection normal to and from the center of the windbreak. Beyond this 30 H length requirement, the length of the plant mass has no effect on the extent of the zone of protection perpendicular to the windbreak.

The maximum leeward drift in this zone has been the subject of much debate. The farthest distance at which some reduction in wind velocity can be found was held to be only 10 H by Flensburg, and only slightly further by Walker; Den Uyl (1936) and Barth put it at 12 H; and Anderson at 15 H. Others have put this distance much further: Bates (1911) at 20 H; Hopkins (1946), Palmer (1918), and Chepil (1949) at 30 H; Woodruff and Zingg (1953) at 27 H; and most Russian researchers at 25 H (although some Russians report a length of 40 H for the zone of influence).* That all of these reports expressed the extent of the zone in terms of barrier heights reflects the fact that the zone of wind velocity reduction remains in a constant proportion to barrier height, regardless of what

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*All the above were reported by Woodruff and Zingg (1953). Flensburg, Walker, Barth, and Anderson had no citations or years for the citations given. We have not been able to secure any material by these four authors.

that barrier height measures. Nothing in the literature contradicts this conclusion, as long as other factors remain constant. Inconsistencies among these researchers in the other important factor, porosity of the barrier, may explain the wide differences in the length of the zone of influence. As will be seen, the porosity of the plant mass can drastically affect the length of the zone of wind reduction, as well as the length of snowdrifting. As has been pointed out by Bean et al. (1975), porosity is the controlling factor for the amount of wind reduction behind the barrier. The vast amount of effort expended in trying to define and measure windbreak porosity indicates its importance.

Porosity is here taken to be a measure of how penetrable a plant mass is to air passing through it. To measure this quantitatively is not a simple matter and to classify plant masses by their porosity is even more difficult. One method that lends itself well to the ranking of plant masses by porosities is one that takes porosity to be directly related to visual porosity. Danish researchers Nokkentved (1938) and Jensen (1954) used photos of plant masses to compare the ratio of open area to filled space. A similar method was used by George et al. (1963). They placed a dotted grid over enlarged photos and then counted the dots that fell on the trunks and branches; then computed the percentage of space occupied to arrive at "density." They claimed reliability of this method when comparing these results to barriers of known densities (presumably fences). Their results (when subtracted from 100% to convert to porosity from density) where, for example, 42% porosity for a single row of Siberian Pea trees and 63% to 90% porosity for a single row of Cottonwoods. Another method based on the correlation between visual "openness" and porosity uses measurements of light transmission to determine porosity (Fryrear 1962; Honda 1974).* As a quantitative measure of visual permeability these methods work adequately. However, since light and wind act quite differently, these methods could be very misleading as a measure of aerodynamic porosity. No complete correlation system to relate visual and aerodynamic porosities has been presented. In an investigation more directly related to wind, Bean et al. (1975), found almost equal values for visual porosity and aerodynamic porosity at high porosities, but greater differences at lower porosities. Their method for determining aerodynamic porosity, and a similar method employed by Grundmann and Niemann (1954) involved the ratio of leeward windspeed to open-field windspeed as a way of comparing windbreaks of different porosities. As pointed out by Van Eimern (1964), however, there are so many other factors that influence velocity reductions behind plant windbreaks besides porosity that this method is not satisfactory. To hold all of these factors (height of measurement, open-field velocity, pressure, etc.) constant in nature in order to determine the precise influence of porosity would prove very difficult and time-consuming.

Another system, developed at least on a theoretical basis by Iizuka (1952), used aerodynamic principles. It involved calculating a coefficient of resistance from the Reynolds number, assuming that the resistance of stems, branches and needles against the wind is similar to that of a cylinder. Then the wind resistance of the whole plant was calculated.

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*Cited in Hagen (1976).

Calculated drag coefficients figure importantly in a method used by Hagen and Skidmore (1971a), Meroney (1968), and Rayner (1962). Wind tunnel test of fences with known porosities (ratio of open area to total surface area) result in drag coefficients correlated to porosities, independent of windspeed. Then, if drag coefficients can be calculated for plant windbreaks from field data, the porosity of those windbreaks can be found. However, Hagen and Skidmore (1971a) point out some restrictions. The first is that while percentage wind reductions behind fences will be independent of open-field wind velocities, this is not necessarily true for all plant windbreaks, due to their flexibility. (This phenomenon will be discussed later.) They also show, based on Woodruff's tests (1963), that drag coefficients for slat type fences would not apply in rating the porosity of very wide shelterbelts. In addition, in order to measure the drag coefficient of windbreaks in the field, certain factors would once again have to be held constant, such as atmospheric stabilities and windward roughness lengths. This was done in a few cases for windbreaks by Hagen and Skidmore (1971a), resulting in porosities being found for one row of Tamarisk of 57% and one row of Siberian Elm of 75%. The other researchers using this method, mentioned above, determined drag coefficients that resulted in varied porosities for individual trees. For example, in the case of a spruce tree one found a porosity of 69% (Rayner 1962) and the other 35% (Meroney 1968).

Although windbreak porosities determined by any one of these methods can not be compared with those determined by another, a relative ranking of windbreak porosities might be achieved using any one of them alone.

However, this would require not only a large amount of data to be collected to minimize differences between individual samples of the same plant species combinations, but also great care that other environmental factors were the same. This mammoth task has not as yet been undertaken, so it seems that using quantitative rankings of windbreak porosities to discover the importance of porosity to snowdrifting is not feasible at this time. However, various qualtative systems have been proposed.

To determine qualitative porosity rankings, categories are established and then defined in terms of particular plant characteristics. Den Uyl (1936) proposed such a system using five categories. Density 1 is nonpenetrable (no porosity) and includes solid barriers such as hills and solid fences or walls. Density 2 is very dense (low porosity) and refers to rows of conifers with low branches that completely fill in the lower levels of the plant mass. Density 3 is medium dense and is defined as mixed plant masses containing both conifers and deciduous trees in full leaf. Density 4 is an intermediate category (more penetrable than impenetrable) containing all types of open form trees and shrubs, either coniferous or deciduous. Density 5 is the most open type, referring to the winter condition of plant masses consisting entirely of deciduous trees or pruned conifers. It can be seen immediately that this system is rather imprecise, and yet is a complete system that lends itself well to relative rankings. A more precise system proposed by Panfilov (1940)* is based on the porosity at different heights in the plant mass. The plant masses with the most porosity are those that are open at all levels

*Reported in Robinette 1972.

throughout their height. These are followed by those with a medium density in the crown region but a very open lower level. Next would be windbreaks with a medium porosity at low levels and a very open crown area (such as a single row of pyramidal conifers with fine-twigged deciduous shrubs underneath), followed by those with a constant medium porosity at all levels that is slightly penetrable by wind. This ranking of levels can go on to the least porous, a plant mass that is impenetrable to the wind at all levels.

Both of these systems are qualitative evaluations based on visual inspection. However, they provide a guide for directly interpreting the physical properties of the plant mass, such as the type of tree (deciduous or coniferous), the existence of shrubs, the spacing of rows and plants within the row, and the like. It may be that, in practical terms, for the purposes of design and plant selection for windbreaks these qualitative systems are all that is necessary. These systems, especially the latter of the two, apply very well to what is known of the importance of windbreak porosity to snowdrift control.

Table 3 lists various plants and plant masses, based on their winter form, in three general categories: low porosity, medium porosity and high porosity. The purpose of this table is to give examples of what is meant by those three broad categories and how similar porosities can be achieved through different combinations of plants. This is true for both coniferous and deciduous trees and shrubs. Figures 15 and 16 show what is being referred to as low plant porosity achieved both by deciduous and coniferous plants, respectively. Figures 17 and 18 illustrate plant masses of medium porosity achieved through deciduous

Table 3. Plants and plant masses catagorized according to porosity.

High Porosity (Open)	Medium Porosity	Low Porosity (Tight and Compact)

Individual Plants Having High Porosity
• Sitka Spruce
• Corsica Pine
• Lodgepole Pine
• Scotch Pine
• Douglas Fir
• White Pine
• Western Hemlock
• Crabapple
 	
Plant Masses Having High Porosity
• High porosity in the crown area with medium porosity in the understory:
  • 2 rows Cottonwood with one row Burning-bush (<u>Euonymus</u>)
  • 1 row Siberian Elm with one row American Plum
• Medium porosity in the crown area with high porosity in the understory:
  • 3 rows Cottonwood
  • 1 row Green Ash, 1 row Siberian Larch, 1 row Horse Chestnut
  • 2 rows Amur Maple, spaced widely
  • 1 row Russian Olive
• High porosity in both the crown area and the understory (uniformly open)
  • 1 row alternating between Cottonwood and Eastern Redcedar with 1 row alternating between pairs of Scotch Pine and Eastern Redcedar (spaced widely and not staggered between rows)
  • 1 row Norway Spruce
  • 1 row broom corn
  • 1 row pampasgrass
  • 2 rows tall wheatgrass
	Individual Plants Having Medium Porosity
	• Juniper
	• Grand Fir
	• White Fir
	• Deutzia
	• Siberian Elm
	• Russian Olive
	• Siberian Peashrub (Caragana)
	
	Plant Masses Having Medium Porosity
	• Low porosity in the crown area with high porosity in the understory:
	  • 2 rows Wayfaring Tree
	  • 2 rows Blackhaw
	  • 2 rows Green Ash, 1 row Boxelder
	• Low porosity in the crown area with medium porosity in the understory:
	  • 2 rows Green Ash, 1 row Boxelder, 1 row Siberian Peashrub
	  • 2 rows Amur Maple with 1 row Burningbush
	  • 2 rows Russian Olive with 1 row common privet
	• Medium porosity in both the crown area and the understory (uniform medium porosity)
	  • 1 row Tamarisk, 1 row Green Ash, 1 row Siberian Peashrub
	  • 1 row Green ash, 1 row Boxelder, 1 row Siberian Peashrub
	  • 1 row Honeysuckle
	  • 1 row Regels Border Privet
	  • 1 row Norway Spruce with 1 row Austrian Pine (spaced widely)
	  • 1 or 2 rows of either sudangrass, grain Sorghum, or forage Sorghum
	  • 2 rows broom corn
		Individual Plants Having Low Porosity
		• Leafy Blackthorn
		• Yew
		• Colorado Spruce
		• White Spruce
		• St. John's Wort
		• Spirea
		
		Plant Masses Having Low Porosity
		• High porosity in the crown area with low porosity in the understory:
		  • 1 row Lombardy Poplar with 2 rows Spirea
		  • 1 row Green Ash with 2 rows Cheyenne Privet
		• Medium porosity in the crown area with low porosity in the understory:
		  • 1 row Norway Spruce, 1 row Austrian Pine (spaced widely) with 2 rows Yew
		  • 1 row Green Ash, 1 row Boxelder with 2 rows of Rugosa Rose
		• Low porosity in both the crown area and the understory (uniform low porosity)
		  • 4 rows Norway Spruce
		  • 1 row Norway Spruce with 1 row Austrian Pine (closely spaced)
		  • 9 rows including 2 Siberian Peashrub, 2 Green Ash, 2 Chinese Elm, 2 Cottonwood, 1 Boxelder
		  • 5 rows including Siberian Peashrub, Juniper, Green Ash, Chinese Elm, Russian Olive
		  • 2 rows Eastern Redcedar (closely spaced)
		  • 2 rows Honeysuckle
		  • 2 rows Tallhedge Buckthorn
		  • 2 rows Spirea
		  • 2 rows Mountain Ninebark

Fig. 15. An example of one type of low porosity plant mass, using deciduous shrubs.

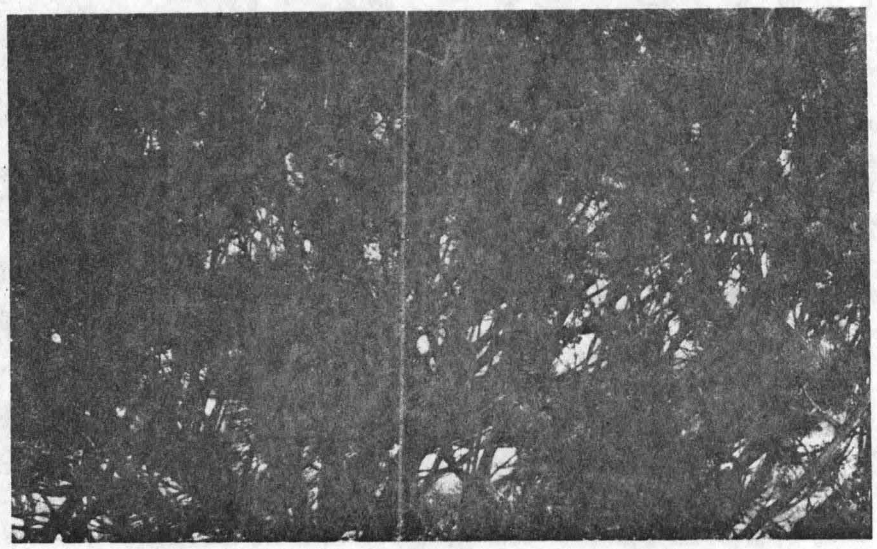

Fig. 16. An example of low porosity plant mass, using coniferous trees.

Fig. 17. An example of plant masses of medium porosity achieved through deciduous plantings.

Fig. 18. An example of plant masses of medium porosity achieved through deciduous plantings.

plantings. Table 3 is based on information reported by the investigators of quantitative porosity rankings listed above as well as on such qualitative evaluations of plant porosities as are available--(Wyman 1969; Hightshoe 1978; I.S.U. Cooperative Extension 1975)--as well as sources already listed. The categories are meant to comply somewhat to the qualitative rankings of Den Uyl (1936) and Panfilov (1940).

It was stated at the beginning of this section that as the porosity of a barrier increases the point at which the maximum reduction in wind velocity occurs moves further leeward from the barrier. An increase in porosity also causes a larger maximum drift length. Closer examination of research on the effect of porosity shows that this statement is true only up to a point and that the ultimate snowdrift pattern has much to do with at what level within the plant mass this increased porosity occurs. First, we will examine windbreaks that have a uniform porosity at all levels.

Wind tunnel tests by Hagen and Skidmore (1971b) of a solid wall show that the maximum wind reduction is at 1 H leeward, where the wind is 30% of the open-field velocity. At 21 H leeward the wind is back to 90% of open-field velocity. They also found that when a fence of 20% porosity was tested, the point of maximum wind reduction was at 2 H. For a 40% porosity fence it moved to 4 H leeward. In tests of reed mats, Naegeli (1953) found a similar relationship. For mats of 15% to 25% porosity the minimum windspeed was measured at 3 H, and this moved to 6 H for 45% to 55% porosities. In comparing these two porosity ranges, he also reported a greater wind reduction at further distances leeward in the case of the more porous barrier; at 26 H the 45% to 55% porous mat caused a windspeed that was 91% of the open-field speed, but only 96% for the 15% to 25% porous mat. There was also a slightly larger reduction at 1 H windward for the less porous mat.

Other investigations show the same general relationships to be true for plant windbreaks. A very dense (nearly impermeable) windbreak dropped the windspeed to about 15% at 0.5 H to 1 H, to 55% at 5 H and a recovery to 100% in the area between 22 H and 25 H. For a dense (partly penetrable) windbreak, the minimum was 25% of the open-field windspeed at 2 H leeward, and the windspeed was still only 33% to 43% at 5 H. It returned to 90% at 20 H and to 100% beyond 30 H. The wind reductions associated with a medium dense plant mass (around 50% porous) were a minimum of 35% of the open-field speed between 3 H and 4 H, 97% at 25 H, and 100% beyond 30 H (Naegeli 1941, 1946). Den Uyl (1936) reported different wind reductions for a very porous windbreak of one row of Norway Spruce as compared to a low porosity windbreak of four rows of Norway Spruce. The windspeed at 2 H leeward in the first case was 53% of open-field wind and 20% in the second case.

This larger zone of protection leeward of a more permeable windbreak is also relfected in snowdrift data. Finney (1934), reporting on wind tunnel tests, shows a slightly larger drift behind a 25% porous fence than a solid one. Similarly, drifts behind very low porosity windbreaks seldom reach beyond 10 H leeward, with the maximum snowdrift depth measured at about 3 H (George et al. 1963). Subin (1960) recorded snow depths within windbreaks and at distances of 10 m leeward that were three times as deep for impermeable windbreaks as for permeable ones; but depths at 150 m leeward were greater for permeable as compared to impermeable windbreaks. A similar situation was found by Naegeli (1953); that is, lesser depths in the windbreak but greater depths at some distance leeward for permeable plant masses. Van Eimern's statement (1964) that impermeable windbreaks drift snow to 2 H to 5 H, while permeable ones cause drifts from 15 H to 25 H also fits well with the information on wind reductions presented earlier. Van Eimern goes on to report on measurements taken by Mastinskaja (1953) showing the position of maximum depth moving from 10 m leeward, to 20 m, and then to 40 m for impermeable, slightly permeable, and permeable windbreaks, respectively, as well as a drift length 50% longer in the last case than the first two. Mastinskaja also reported a more gradual rise up to the maximum depth for the permeable windbreak.

Another effect of increased porosity in a windbreak is evident in the windward drift. An impermeable barrier creates low and short windward drifts, while a slightly permeable belt has a longer windward drift (Mastinskaja 1953). Van Eimern (1964) reported on measurements of a drift to 6 H windward of a three-row pine windbreak with a uniformly low porosity. This effect is sometimes evident as equal windward and leeward drift lengths in the case of a three-row deciduous windbreak compared to a five-row deciduous windbreak where much more of the drifting was leeward (Vysockkij 1938).* These windbreaks, however, were of a medium porosity or even an open porosity. The width of the windbreak also has some effect on where the snow will drift, as will be discussed later.

*Reported in Van Eimern (1964).

A comparison was made of two separate one-row Siberian Elm windbreaks, one with trees 1.5 m apart, the other with trees 3 m apart (Frank and George 1975). A drift formed at 6 H windward of the first windbreak (with less porosity), rising to its maximum of 2.4 m deep at about 1.5 H leeward, and ending at 11 H. The drift at the other row began at 10 H windward and rose to a maximum of only 1.5 m deep at about 3 H leeward and ended at 15 H leeward. Here the increase in windward and leeward length and decrease in maximum depth seems to be a result only of greater porosity.

Generally speaking, as the porosity in a uniform windbreak increases from no porosity to medium porosity (about 50%) the following changes will occur in snowdrift configuration. The point of maximum depth will move to a greater leeward distance; the overall length of the drift leeward will increase; and more windward drifting will occur. Also the drift will have a more gradual rise to the point of maximum depth.

These effects on wind and snow deposition result when porosities are increased from very low porosities to the medium porosity range, around 50%, and when this porosity is uniform at all levels of the plant mass. They do not hold true for high porosities, above 60% or 70%. The report by Hagen and Skidmore (1971b) shows that the point of maximum wind reduction for a 60% porous fence is at 6 H leeward, but that the wind has recovered to 70% of open-field velocity at 14 H. This 70% was observed at the further distance of 17 H for fences with 20% and 40% porosities. This indicates that the length of the leeward zone of the wind reduction does not continue to increase as the porosity increases beyond 60%. Measurements behind tree windbreaks support this conclusion. At a distance of 20 H leeward of a plant windbreak of medium porosity, the wind was 85% of the open-field velocity as compared to 92% the same distance leeward of a plant windbreak with open porosity. The more porous windbreak also had a shorter overall zone of protection (25 H to 27 H) than the medium porosity windbreak, which was 30 H (Naegeli 1946).

The amount of wind reduction is, as expected, less behind a very open windbreak. One row of Norway Spruce caused a reduction of 53% at 2 H leeward, while four rows of Norway Spruce created a reduction to 20% (Den Uyl 1936). Naegeli (1946) reported wind reductions between 14% and 17% for a very dense windbreak and between 37% and 39% for a loose windbreak, although this value is not much higher than the 34% to 38% of open-field wind which is the maximum reduction associated with plant masses of a medium porosity. The shelter behind a porous windbreak was measured by Miller et al. (1975). It consisted of one row alternating between Cottonwood and Eastern Redcedar 1.8 m apart, and then another row 3 m away of alternating pairs of Eastern Redcedar and Scotch Pine. These two rows were not staggered. The wind was reduced only to between 60% and 70% at 2 H and to between 80% and 85% at 8 H leeward, with a measurable effect extending to 14 H. One row of Cottonwood reduced winds to only about 80% at 2.5 H compared to 68% at 2.5 H for one row of Green Ash, a less porous windbreak (George et al. 1963).

With a shorter zone of wind reduction a shorter leeward drift is also expected. Finney's wind tunnel tests (1934) of fences showed a drift to 10 H for a 60% porous fence and to about 14 H for a 25% porous fence. The point of maximum snowdrift depth was measured within the row when one row of Siberian Elms was examined, but the drift ended between 5 H and 9 H. It also did not trap a large amount of snow overall (Frank et al. 1976). However, Woodruff (1954) reported that the drift behind two rows of deciduous trees (without leaves) began at 8 H, reached its maximum depth at 17 H and ended at 25 H. For a five row deciduous windbreak the drift began at 2.5 H windward, was at its deepest at 3 H leeward and had ended by 17 H. The trend for a shorter leeward drift associated with very open porosities seems to be contradicted by these last measurements.

One reason may be the lack of a uniform porosity at all levels. The effects being discussed thus far occur only when the porosity of the windbreak changes equally at all levels. Some researchers believe, however, that the stem area of hardwood tree rows is the crucial factor in wind reduction (Bean et al. 1975). While a somewhat impermeable windbreak may cause the drift to begin within the windbreak or on its leeward edge, a high porosity lower level can cause 60% to 80% of the snow to drift further leeward (Read 1964). This is not surprising when one considers the change in aerodynamic patterns this lower level open porosity can cause, as well as the way snow is transported. The densest snow/air currents usually are within the 2 m closest to the ground, with 80% of this snow occurring within the lower 4 cm (Jumikis 1970). Not only will wind currents passing through a stem-gap area carry more snow, there is a possibility that the wind speed directly leeward at this low level could increase to 115% of open-field velocity (Naegeli 1941).

In testing the wind reductions caused by different porosities in the stem areas of plant masses, a windspeed that was 70% of the open-field velocity was found at 1 H, and 60% at 3 H, leeward of a dense stem area (27% visual porosity). For a medium porous stem area (48% visual porosity), the values were 60% at 2 H and 65% at 4 H; and for an open stem area (80% visual porosity) 80% at 1 H and 95% at 5 H (Bean et al. 1975). Once again with very high porosity, a shorter zone of protection and less total reduction is the general rule. As for snowdrifting, Frank and George (1975) checked on the effect of pruning the lower branches of one row of Siberian Elms (already a highly porous windbreak). Without pruning, it caused a drift from 2.5 H windward to 5.5 H leeward, with the maximum depth at the leeward edge. (See Fig. 19.) With the lower 0.76 m pruned of branches, the drift began in the windbreak, reached its maximum depth at 6 H, and ended at 10 H. The same configuration occurred with the lower 1.4 m pruned, but with less snowdrift depth. A more extreme example of this effect of high porosity at low levels in the plant mass is given by Stoeckler and Dortignac (1941). A somewhat dense windbreak of several rows of Siberian Pea, Golden Willow, Chokecherry, Wild Plum, Silver Buffaloberry, Lilac, Russian Olive and Honeysuckle caused a maximum snowdrift depth of 120 cm to 300 cm between 9 m and 24 m leeward. Three rows of Cottonwood 18.3 m tall with no branches below 6 m caused maximum depths of between 15 cm and 60 cm between 90 m and 115 m leeward. The drift did not end unitl it reached 280 m (about 15 H). Figure 20 illustrates the long, low drift associated with such plantings having open lower levels. Note the deeper drifts caused by some low shrubs and the lack of windward drifting.

In more closely examining the effect of porosity changes at different levels within the plant mass, Iizuka (1952) concluded that the porosity of the stem zone had little effect beyond 10 H leeward and that differences in the porosity of the stem area and crown region were insignificant beyond 13 H. The importance of the crown region porosity

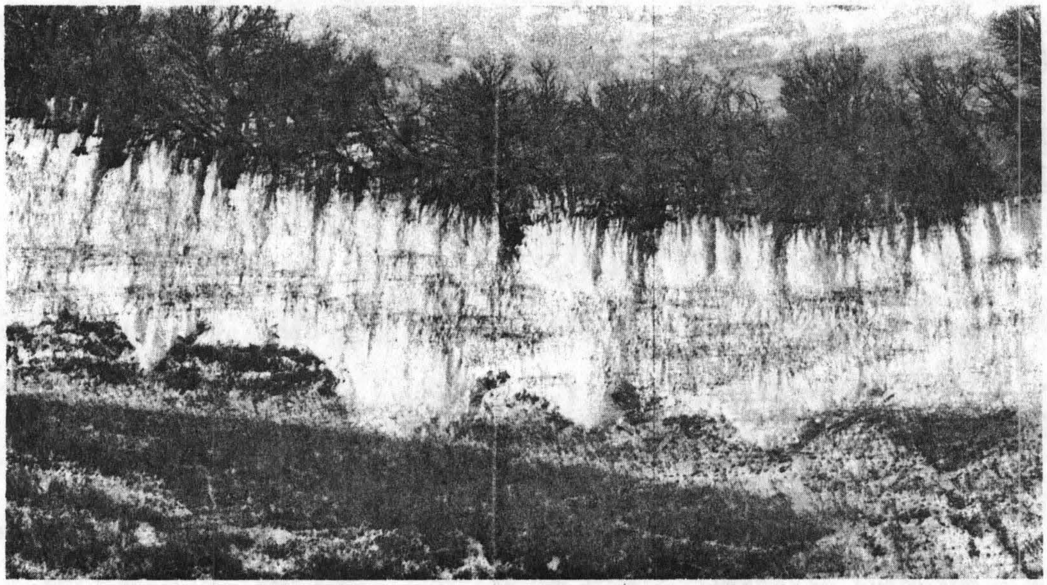

Fig. 19. An example of a planting creating drifts similar to those described by Frank and George (1975).

Fig. 20 . Typical snowdrift.

alone is most noticeable beyond 8 H. This crown porosity effect is important when considering single row evergreen windbreaks, due to the pryamidal shape of some evergreens.

It may not be possible to predict precisely what the effect on snow-drifting of particular porosities will be. However, experience has shown some optimum porosities for snow storage. Optimum snow storage is here taken to mean storing the most amount of snow near a windbreak of a given height and width. Hagen and Skidmore (1971b), who tested fences of many different porosities, found that the lowest windspeeds were distributed over the largest area leeward of a 40% porous fence. These windspeed reductions were from 5% to 10% larger in this case than the other porosities. Other researchers, such as Blenk and Trienes (1956), have found the maximum sheltered area to be associated with porosities of 35% to 50%.* Tabler (1978b) states that 50% is the optimal porosity for snow storage, and this is generally borne out by the other studies reviewed. The plant mass should also have a uniform porosity at all levels, created by many small openings rather than by large gaps (Miller et al. 1975; Naegeli 1946; Nokkentved 1938). This points to one advantage of plant windbreaks as opposed to fences for optimal snow storage. Woodruff (1954) states that even the poorest shelterbelt has a capacity for snow storage that is 135 times as great as that for a solid wall, and that the best shelterbelt has a capacity 36 times as great as the best snow fence.

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*Reported in Plate 1970.

Optimum snow storage, or the most drift for the height of planting, may not always be the goal. In many cases, the desire is to confine the drifting to whatever space is available due to other constraints. Within limits, it is possible to design a windbreak to create drifting to fit particular conditions. This will be discussed at the end of this section. First, it is necessary to discuss several other factors that influence snowdrifting.

The final physical characteristic of a plant mass that affects snow drifting is its width. In some respects, an increase in width of the windbreak has the same effect as decreasing the porosity (which is a physical change in the windbreak accompanying increased width). The pattern of wind reduction leeward of a ten-row deciduous windbreak with leaves is similar to the pattern for a solid wall. Although a solid wall causes a reduction in windspeed to 25% of open-field velocity at 13 H leeward (at 10.6 H for the ten-row windbreak), they both are effective out to about the same distance. It should be noted, however, that the zone of protection for a ten-row windbreak without leaves is much shorter than for the solid wall (Woodruff 1954). This may be caused by high porosity within the lower level of the plant mass. As the width drops, the windspeed reductions change as they do when porosity increases. A 5-row windbreak without leaves, consisting of one row Green Ash, two rows Siberian Pea tree, and one row Boxelder, was able to reduce the wind only to 66% and its zone of protection was found not to extend much further than 20 H (George et al. 1963). This pattern is similar to that found leeward of fences with more than 60% porosity or 1- and 2-row windbreaks of an open nature, as reported earlier.

Changes in the drift patterns of snow due to changes in width are also somewhat similar to changes in porosity. Very wide barriers tend to form drifts that have their maximum depth in the barrier or just leeward, as seen in reports on a 8-row windbreak by Stoeckler and Dortignac (1941), a 13-row windbreak by Vysockkij (1938), a 10-row windbreak by Woodruff (1954) and a 9-row windbreak by Potter et al. (1952). This last report shows how the point of maximum depth moves further leeward as the width decreases. However, the overall drift length leeward is seen to be longer in the case of these wide windbreaks than in the case of dense, narrow windbreaks and solid walls. The above 10- and 9-row windbreaks caused drifting out to 15 H and 13 H, respectively. As the width decreases, the leeward length of the drift does not correspond to the more porous-type tree windbreaks for which the wind velocity reductions were similar. The 1- and 2-row open-type windbreaks referred to above as having a similar leeward wind reduction pattern as a 5-row leafless belt only drift snow to between 5 H and 9 H. Woodruff (1954) found a 5-row leafless belt to cause drifting to about 17 H. Potter et al. (1952) found the drift leeward of a 5-row deciduous windbreak to extend to 11 H. Decreasing the porosity of this windbreak without increasing the width (by replacing a tree row with a row of Juniper) did not change the drift length leeward, although the windward drift length did get shorter. This windward drift is important in a wide shelterbelt. The above 5-row plant mass with Junipers caused a windward drift to 3 H. Windbreaks of increased width often have longer windward drifts, to 13 H windward for a 9-row deciduous windbreak (Potter et al. 1952) and 10 H windward for a 5-row windbreak (George et al. 1963). The total amount of snow deposited increases with wide belts as shown in research by Golubeva (1941), who found much greater snow depths with an 8-row windbreak than with a 2- or 4-row windbreak.

Changes in the width of a windbreak seem to have a similar effect on wind velocity reduction as changes in its overall porosity. Increasing the width of the windbreak may actually increase the amount of snow deposited and creates windward and leeward drifts that are nearly the same length. However, wider windbreaks do consume greater amounts of space, which could be a very important consideration in some situations.

2.3.3. Other Factors Affecting Snowdrifting Near Plant Masses

The effectiveness of a windbreak in trapping snow can be influenced by conditions independent of the physical properties of the plant mass. These conditions include wind velocity, surrounding terrain, and adjacent ground cover.

Wind Velocity

The effect of wind velocity has been the subject of much discussion, and some confusion. In 1934, Finney stated that the position of maximum drift depth moves closer to a solid fence both windward and leeward as wind speed grows larger. He also stated in a later publication that for porous barriers higher winds carried the snow away from the fence (1937). Woodruff and Zingg (1953), on the other hand, maintained that the percentage reduction in wind speed is independent of the original wind speed. Tabler (1978b) states that for the range of wind speeds during which blown snow events occur (8 m/sec to 35 m/sec), drifting configuration does not change significantly. A Highway Research Board report (National Research Council 1956) on using plants for snow control states that high winds have little effect on the drifting area, but that they will cause the drift itself to form closer to the leeward side of the barrier. This somewhat confusing situation can be illuminated by considering the different effect wind can have on plants and fences. Van Eimern (1964) pointed out the possibility that although the higher wind speeds may not directly affect wind reductions in the lee of plant masses, increased winds can change the porosity of the plant mass. Experimentation by Woelfle (1939) confirms that porosity diminished in Spruce barriers as the wind speed increased. But there is another effect of higher wind speeds, pointed out by Meroney (1968) in reviewing much of the past literature as well as tests on actual trees: "Self-streamlining of the tree at high velocities can reduce effective cross-sectional area for the more flexible species." This streamlining is reflected in results of experiments to determine drag coefficients of tree windbreaks by Mayhead (1973) and Rayner (1962). Both report lower drag coefficients at higher wind speeds.

Although these effects may still not be conclusive as to how windspeed affects snowdrift patterns, some applications are possible. For example, a belt that may be too open to give protection (and significant snowdrifting) at lower speeds could give better results at higher speeds (Robinette 1972). Naegeli (1946) points out that in areas with higher average wind speeds, the relative protection given by dense and very dense windbreaks is greater than it would be in areas of lower windspeeds. Iizuka (1952) points out that crown area width and low porosity become an advantage in heavier winds. Such decreases in porosity might possibly be considered in selecting species based on plant shape, as well as in setting distances between trees.

It seems now that increased windspeed will have an effect on plant windbreak snowdrifts, but not on snowdrifts associated with fences. However, there are enough contradictory reports to warrant more research, which should further understanding of why such changes occur.

Terrain

Terrain is another condition that affects windbreak performance. Hunter (1962) and Finney (1934) both show the effect grade changes alone have on drifts. Basically, high, steep cuts cause shorter drifts and, below a point, flatter grades reduce drifting substantially. Proper positioning of plants with respect to these steep cuts can increase snow storage volume and to some extent can shorten the drift length that may be expected by a windbreak alone. A recent example of this is in the design of snow control plantings along I-35 in Minnesota (Minnesota Department of Highways 1975). After the cut area is full of snow, if there is sufficient additional snow, the drift pattern will grow from there as it would without the cut. For hilly terrains in general, Naegeli (1946) reports that zones of protection will be shorter than those associated with windbreaks on flat terrain. This is due to the increased turbulence in the open-field flow. Tabler (1978b) reports that in some cases there is an increase in windward snow deposition in hilly areas. This would depend somewhat on the orientation of the windbreak and its placement on the hills.

Ground Cover

The turbulence in open-field wind referred to above can also be increased by ground cover texture. This is true because of the effect on the roughness height (z_o), which many researchers have deemed important in explaining how windbreaks work (e.g., Hagen and Skidmore 1971b; Van Eimern 1964). Van Eimern reports that generally a rough surface upwind causes the point of maximum wind reduction to move closer to the belt, and, as a matter of fact, compresses the entire leeward wind distribution curve. (Incidentally, wide differences in ground cover conditions may go a long way towards explaining discrepancies in field data reported for similar windbreaks.)

Ground covers and grasses themselves can be useful in snow control as well, especially when the heights that native grasses and crops can reach is considered. Smika and Whitfield (1966) found that small wheat stubble was effective in trapping snow. Greb and Black (1971) have done considerable research on using tall wheatgrass barriers as snow traps. They tested double rows of wheatgrass that grew 1.2 m to 1.4 m tall with an air porosity of about 65%. These were tested with both 9.1 m and 18.3 m spacings between double rows. Average snow depth was 20 cm to 38 cm deeper than normal accumulations within these intervals. They also tested various rows of corn, sudan grass and sorghum varieties. They found that sudan grass performed well as far as resistance to snow lodging within the plants, strength, ease of growth, and flexibility were concerned. They concluded that porosities of 65% to 75% were the optimum for drifting snow as far leeward as 12 H. Others have researched similar systems, as well as porosities of plant masses of grass and crops (Fryrear 1962).

Roughness fields (on-going experiments by Tabler 1978b) are also effective in trapping snow. Arrays of round poles with particular frontal area to surface area unit ratios are now being examined, which could lead to experimentation with dense shrubs planted in widely spaced arrays as well.

All of these systems are applicable only to situations where there is sufficient open ground area available to make the shallow snow storage significant, such as interstate interchange areas, for example, or large open fields where they are presently used to enhance moisture retention. There are other ways in which particular plant configurations can make the snow deposition area fit within given constraints. This will be discussed in section 2.3.4.

2.3.4. Using Plant Masses to Control Snow

It is by now apparent that there are many factors determining how plant masses induce snow deposition and that the application of these factors to individual situations is a complex problem. Gordon Hunter (1962) outlined a simple procedure to help predict where the worst snow-drifting problems are likely to occur. This procedure involved combining what is known about wind directions in an area with an understanding of factors contributing to snow drifting (such as those discussed above), including types of cuts, upwind ground condition, and location of plantings adjacent to roads. The Minnesota Highway Department (1975) used a more complex procedure to locate problem areas on I-35 and went on to develop planting schemes that fit the particular conditions in those areas. Especially important in their designs was proper location of plantings with respect to cut slopes, since the beginning and end of cut areas were found to cause the most severe maintenance problems. The placement of plantings with respect to cuts greatly increased the snow storage capacity in a limited right-of-way (Minnesota Department of Highways 1975). Space limitations in flat areas can also be dealt with by specific planting configurations.

A frequent limitation is the lack of space sufficient for many rows of plants. Woodruff (1954) found that a substantial drift was created leeward of a windbreak of two rows of deciduous trees. This drift did not begin until a distance of 8 H and reached to 27 H, with its maximum depth being reached at 17 H. This long leeward extent of drifting is most likely caused by the open lower levels common to deciduous trees. If a drift closer to the plant mass is what is needed, then a row of low shrubs can be planted along with the deciduous trees. An example of this in Iowa would be two rows of Amur Maple (Acer ginnala) or of Russian Olive (Elaeagnus angustifolius), either of which will provide medium porosity in the crown region. This can be combined with either Mountain Ninebark (Physocarpus monogynus) or Clavey Honeysuckle (Lonicera xylosteum, "Claveyi") to provide medium to low porosity in the lower level of the plant mass.

Another possibility for creating a windbreak using smaller amounts of space was reported on by Den Uyl (1936) and Bates (1911). They both reported significant reductions in wind velocity leeward of low porosity windbreaks made up of two rows of closely spaced evergreens. The snow storage value of such a windbreak is illustrated in Fig. 21. The amount of snow storage leeward of such a compact plant mass of two tree rows will not be as great as those having combinations of trees and shrubs,

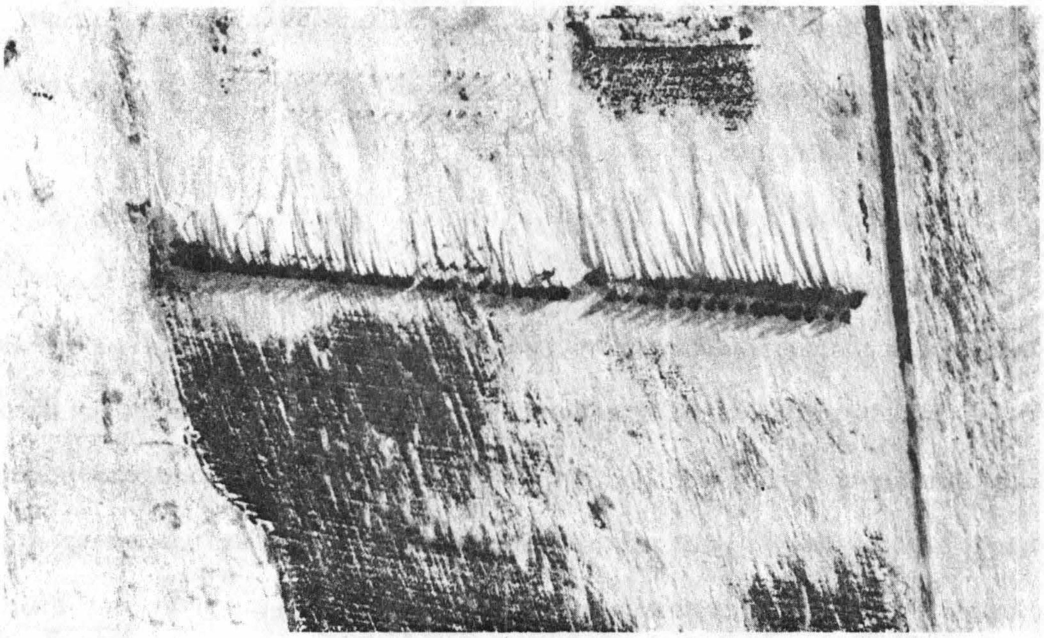

Fig. 21. Snowdrifting leeward of one and two rows of combinations of young Austrian and Scotch Pine. Note the greater snow deposition to the right (leeward of the double-row part of the barrier.)

which together create a medium porosity level. However, storage will occur closer to the windbreak. A compact windbreak of only two rows is very vulnerable to gaps forming if one or two trees do not grow. This can be a problem when using Austrian, Norway, or Scotch Pine, due to their relatively specific drainage and soil requirements. Using White Pine exclusively can be a problem also, due to its susceptibility to drying out from severe winter winds. A low porosity barrier can also be formed by using two rows of Eastern Redcedar (Juniperus virginiana) planted close together. This native species is very hardy in the winter, grows well under a variety of conditions, and has the added advantage of being self-regenerating.

The efficiency of a 2-row windbreak for snowdrifting can be increased by using a variety of species and heights within the rows to create a rough surface or sawtooth shape at the top of the plant mass (Robinette 1972). Blenk and Trienes (1955) and Naegeli (1953) report a longer leeward zone of protection with windbreaks whose tops are not rounded.

Another narrow and compact barrier could contain one or two rows of tall high-branching shrubs surrounded by low, bushy deciduous or evergreen shrubs. Siberian Peashrub (*Caragana arborescens*) is a tall shrub often used in this application, especially in the Great Plains. Other suitable tall shrubs would include Tallhedge Buckthorn (*Rhamnus frangula* "*columnaris*"), Cheyenne Privet (*Ligustrum vulgare var.*) and various lilacs. Low shrubs with a variety of porosities can be chosen, such as very low porosity Junipers (which may be susceptible to damage from snow lodging in them) or medium porosity deciduous shrubs such as Bridalwreath Spirea (*Spirea prunifolia*), Vanhoutte Spirea (*Spirea vanhouttei*) or Mountain Ninebark. If space constraints are very severe, several rows of tall shrubs alone can also be used, although the porosity of the plant mass will be more open and the drift somewhat longer.

The shape of the drift can be controlled to a great extent by the planting arrangement. For example, long, low drifts can be created by using single rows of widely spaced evergreens; low, broad deciduous shrubs; or scattered groups of trees and shrubs (Highway Research Board 1956). One application of such a drift configuration would be where long range sight distance is required. As mentioned earlier, a long drift results from plant masses in which the lower levels are open (Stoeckler and Dortignac 1941). This can be achieved either by selecting species of trees whose lower branches fall as they grow in height or by pruning. Such a drift configuration would be useful where there is a walkway very near the leeward side of the plant mass.

The most common case where there is a need to control the shape of the drift is in situations where there is little space available either for the plants themselves or the drifts. It is then advantageous to induce drifting close to the windbreak and to keep the entire drift length shorter. As Finney pointed out in 1937 a tight barrier of closely-spaced trees will achieve this and is particularly applicable to highway rights-of-way. It is necessary that the trees used are branched close to the ground, leaving only a 30.5 cm to 46 cm space at ground level. An example of such a plant mass consisting of evergreen trees is shown in Fig. 22.

An example of a relatively short, deep drift formed behind a windbreak is shown in Fig. 23. Field surveys conducted in conjunction with this project indicated that three rows of Concolor Firs will create a short but deep drift leeward with very little windward drifting. Such a configuration can also be expected when planting close together several rows of finely-branched deciduous trees or shrubs that have branches growing low on the trunk or have more than one stem. In Iowa, this would include Washington Hawthorn (Crataegus phaenopyrum) and various viburnums such as Arrowwood (Viburnum dentatum), Wayfaring Tree (Viburnum lantana), and Blackhaw (Viburnum prunifolium). (These plants,

Fig. 22. Evergreen barrier.

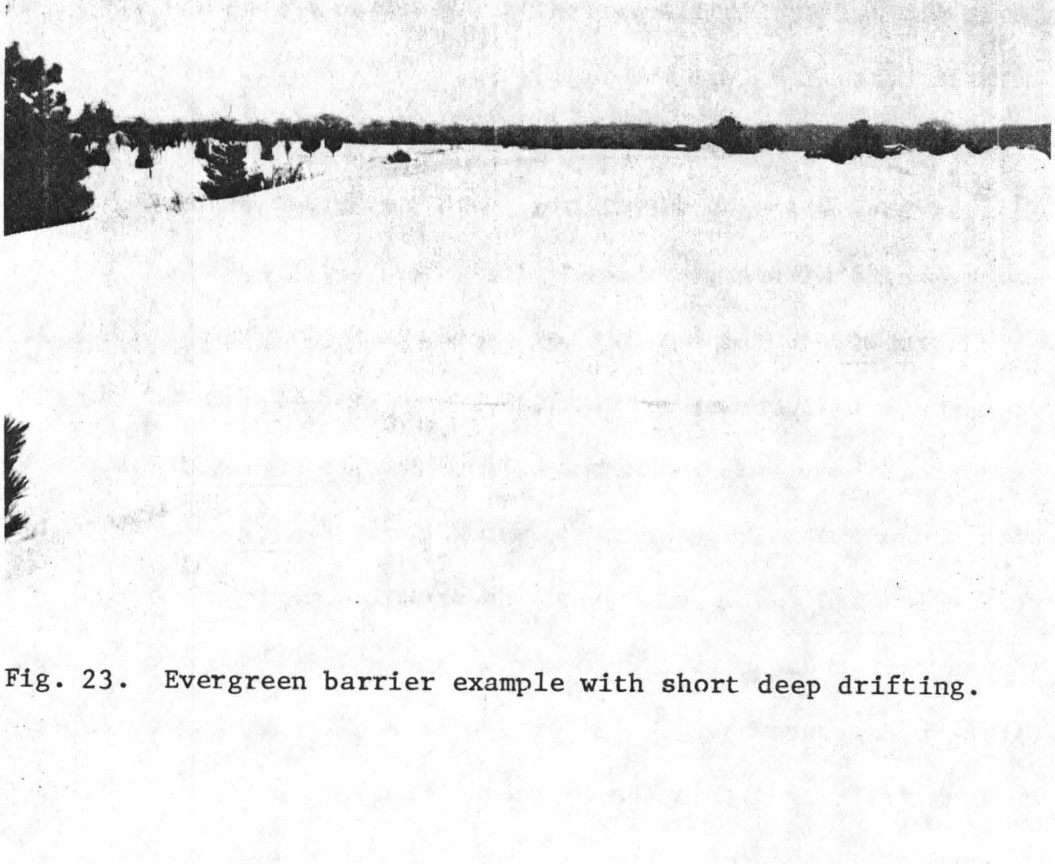

Fig. 23. Evergreen barrier example with short deep drifting.

particulary the Hawthorn and Blackhaw, have a high wildlife value as well.) In situations where there is little room for drifts to form without causing problems, compact, deciduous plant masses have the advantage of drifts forming within the rows. Since the leeward drift length is always affected by the height of the plant mass, another possibility is to use deciduous plants that are even shorter than these small trees. Plants particularly suitable for low porosity, confined windbreaks are Dwarf Korean Lilac (Syringa palibiniana), Beauty Bush (Kolkwitzia amabilis), Japanese Rose (Rosa multiflora), and Zabel Honeysuckle (Lonicera zabeli). Unfortunately, Japanese Rose is so prolific that it can require constant maintenance to keep it from spreading into the snowdrift area. In field surveys, single rows of low porosity Honeysuckle caused drifting to between 4 H and 5 H (although it was not an equilibrium drift and could eventually grow longer) with depths up to 1 H (see Fig. 24).

Like the small trees mentioned earlier, all of these deciduous shrubs will have drifting within the plant mass, adding to the snow storage capacity with a short drift (see Fig. 25).

Drifting within the barrier can be very useful where little leeward space is available. Another plant mass examined in the field consisted of one row of American Plum and one row of Christmas Berry, with a maximum height for the mass of about 10 ft. The drift extended to 5 H leeward (on level ground) and had its maximum depth of 4 ft in the barrier and out to 1 H leeward. There was almost no windward drift. Other researchers have found particular configurations to cause the maximum drifting within the barrier. One such example involved one or

Fig. 24. Short, deep drift leeward of one row of Honeysuckle.

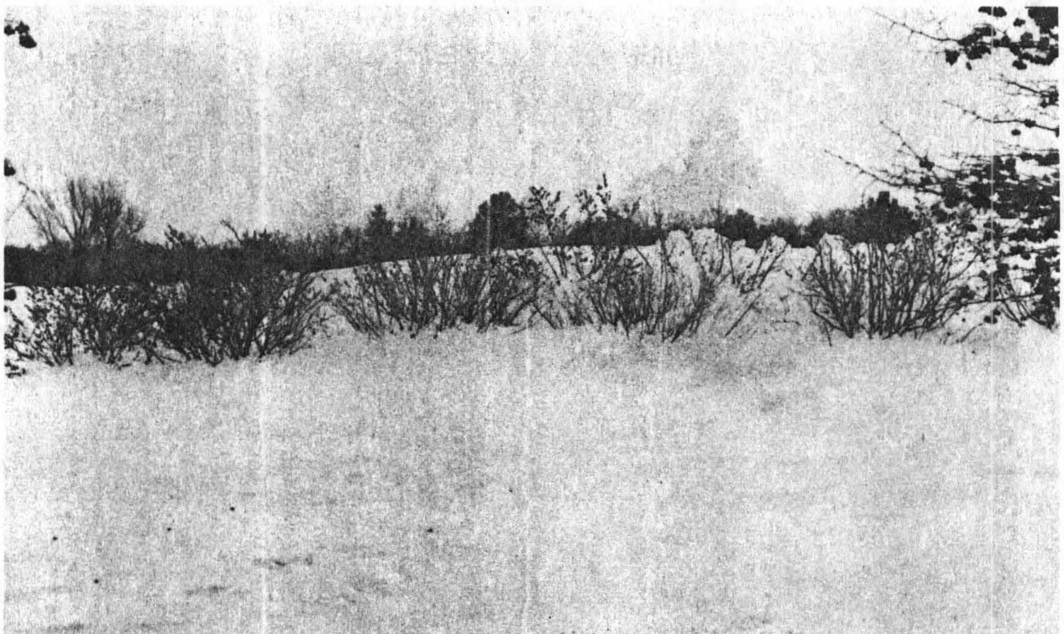

Fig. 25. Deciduous shrub barrier.

two shrub rows on the windward side, then several rows of medium and tall trees, and one row of evergreens on the leeward side (Patten 1956). The Minnesota study also referred to the value of such configurations in inducing drifting within the barrier (Minnesota Department of Highways 1975). These arrangements are similar to a "snow trap," which also has several shrub rows on the windward side. If space is available, an open space as wide as twice the height of the shrubs should be left between the shrub and tree rows (Read 1964). Snow will then accumulate in this space and in the tree rows. If the shrub rows are leeward of the trees they may tend to get excessively lodged with snow, which could damage the plants (see Fig. 26).

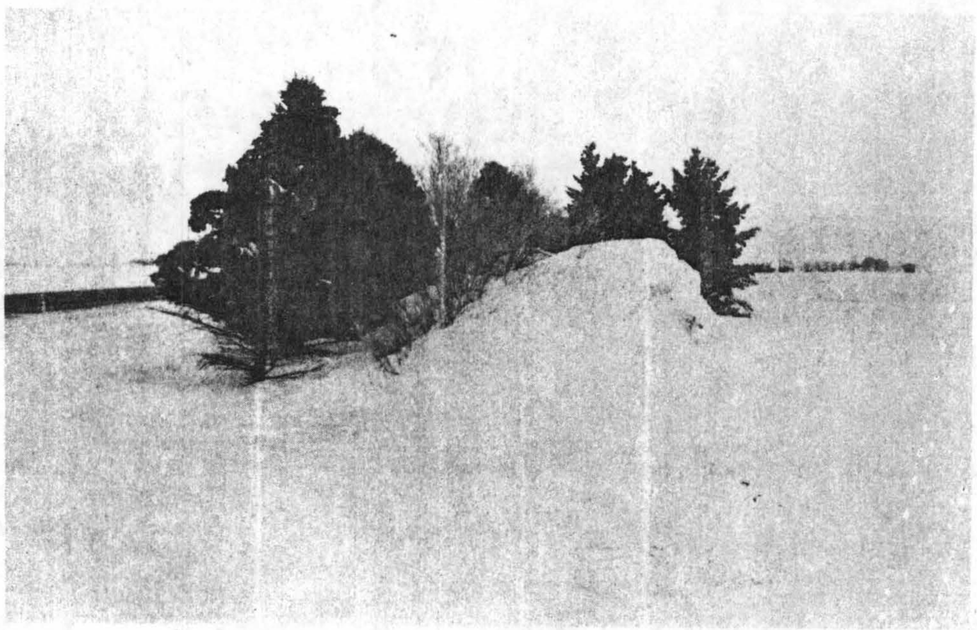

Fig. 26. Deep snow deposits on shrubs.

Kuhlewind (1955) reported maximum snow accumulations between two shrub rows 2 m tall and 15 m apart. Although the drift began at 5 H windward and ended at 15 H leeward, the depths were much greater within the gap and within the second hedge. A similar result was recorded for a windbreak consisting of three rows of Siberian Pea trees and three rows of Boxelder with a 6 m wide open space between the rows. A 1 m maximum depth was measured between the rows, but more significantly the drift began at 1.5 H windward and ended at 1.5 H leeward.

A combination of plants to create a "snow trap" that would be more suitable for Iowa might consist of one or two rows of Clavey Honeysuckle on the windward side and two rows of Eastern Redcedar placed close together on the leeward side. The two species should be separated by an open space of about 3-4.5 m.

In selecting plant species for windbreaks for particular situations, changes in the physical characteristics of the plants as they grow must be considered. For quick effect, fast growing species that quickly attain their maximum height should be used on the outside rows with slower growing species in the center rows. In this manner a uniform porosity will be created very early by the combination of both types. As the fast growing, tall species age they can be removed and shrub rows planted in their place to provide the lower level mass that will be needed as the slower growing varieties reach some height. If there is not enough room for this many rows, two rows of slower growing trees can be planted at first, then followed by shrubs below that at a later time (Read 1964). When planting only two rows, greater uniformity is produced by staggering the two rows. Such narrow windbreaks are vulnerable, because gaps can form if one or two trees die out. Such gaps will cause a much shallower and longer drift downwind from the gap. This problem is greatly reduced if dense shrub rows are included in the plant mass (Potter 1952). Such shrubs can be cut back periodically to assure that they maintain their low porosity over many years time. The usual factors having to do with soils, drainage, and availability of sunlight must also be taken into account when picking plant types. However, within these constraints, many different possible plantings are still available to fit the particular snowdrift problem to be solved.

2.4. The Use of Snow Fences for Snowdrift Control

Artificial devices such as snow fences have been used for snowdrift control for a long time. There are three primary types (Martinelli 1973; Pugh and Price 1954): the collecting fence, which is a solid or porous barrier that decelerates the wind speed in an area providing for deposition; the solid guide fence, which is aligned at an angle to the wind (in plan) in order to deflect the snow laterally; and the blower fence, which is aligned at an angle to the wind (in elevation) in order to accelerate the wind speed locally and cause the snow to deposit elsewhere. By far the most used and usually most practical fence is the collecting fence, which is used to collect and deposit snow upwind of a region (such as a roadway) desired to be kept free of snow deposition.

The collecting fence has been studied fairly extensively at full scale in the field and, to a lesser extent, at model scale in a wind tunnel. Nokkentved (1939) and Finney (1934, 1939) were among the first to study snowdrifting features at small scale. Many of Finney's results are still used and his efforts at understanding the physics of drifting snow resulted in a considerable contribution. Some of his results may be somewhat in error quantitatively (but not necessarily qualitatively) because his wind tunnel experiments were performed before it was known how to properly simulate atmospheric surface winds in the wind tunnel, and also because the similitude of drifting snow modeling was ignored.

Although there is some disagreement among various investigators as to the drift geometry one can expect from a given type of snow fence and also as to what constitutes an optimum fence geometry, there are some data available which appear to be fairly reliable. Pugh and Price (1954) list an equation for drift length as a function of fence height and fence porosity which appears to be valid for a 50% porous fence but not for a solid fence. The leeward drift length for a solid fence is on the order of 10 times fence height (H) (Martinelli 1973) for a bottom gap of 0.1 H and increases as the fence porosity increases. Martinelli quotes maximum drift depth as 0.9 H to 1.1 H. The location of maximum depth is located at 2 H to 3 H leeward of the fence for the solid fence and moves downwind as either porosity or gap distance increases. The maximum depth is located at 8 H for a 40% solid fence with a 0.1 H gap.

Tabler (1978) states that the optimum fence (maximum storage capacity) is a horizontal slat fence with 50% porosity (15.2 cm slats and intermediate gaps) and with a bottom gap of 30 to 46 cm. The fence should incline downwind at 15 deg from the vertical and should be at least 30 H long. For such a fence (from 1.8 to 3.7 m in height), the leeward drift length at saturation is 27 H, the maximum leeward depth is 1.2 H and the cross section area of the leeward drift (perpendicular to fence) is 18 H^2 (Tabler 1979). The windward drift (if it develops) can grow to a length of 10 H, a depth of 0.4 H, and a cross-sectional area of 2 H^2. This information is for a fence on level, flat terrain. (Nokkentved, 1939, apparently was the first to suggest that the cross-sectional area should be proportional to H^2.) Equations for drift depth as functions of distance from the fence are presented by Tabler (1974, 1979). The downwind tail slope on level terrain is 8.3% (Tabler 1974).

Information on drift lengths and depths can be found in Tabler (1974, 1975, 1978, 1979), Martinelli (1973), and Pugh and Price (1954). The effects of gap distance and fence porosity are illustrated by Martinelli (1965, 1973, 1975) and by Pugh and Price (1954). The leeward drift length, of course, is a function of time. Prior to the attainment of an equilibrium drift (saturation) the leeward drift ends abruptly with a sometimes nearly vertical downwind facing wall and with a cornice at the leeward end of the drift. Tabler (1979) presents information on drift length and depth as a function of the degree of saturation ($A/18\ H^2$). He also presents data on the cross-sectional area as a function of distance from the end of the fence and as a function of the wind departure angle (deviation from direction perpendicular to the fence line). Discussion of the drift shape prior to equilibrium or saturation is given by Jumikis (1970).

The effect of topography is very important in the determination of the storage capacity of a snow fence. Tabler (1974) presents the following rules.

1. For gently rolling topography (20% slopes or less) with gentle to moderate slopes, fence performance is affected by the terrain from 45 m upwind to 90 m leeward.
2. On uniform slopes of less than 10%, the fence storage capacity is the same as on level terrain.
3. Depressions in the lee drift zone augment capacity. The equilibrium profile remains the same with respect to the extrapolated horizontal surface.
4. A downward slope in the lee drift zone increases capacity by about 15 to 20% for each degree of slope.
5. An upslope in the lee drift zone decreases capacity.
6. An upslope to windward of the fence increases capacity about 15% per degree of slope. Thus, the most efficient fence is that placed on the top of a rise or on a ridge. The maximum depth, length, and cross-sectional area can all be significantly greater than for level terrain.

Martinelli (1973, 1975) and Schmidt (1970) present the effects of local topography on drift cross section shape and length for somewhat larger slope percentages.

Tabler (1975) has also derived equations based on field measurements which predict snow-drift depositions in depressional areas without snow fences. The equation is

$$Y = 0.25\ x_1 + 0.55\ x_2 + 0.15\ x_3 + 0.05\ x_4$$

where Y is the snow slope (%) over the main portion of the drift, x_1 is the average ground slope (%) over a distance of 45 m upwind of the topographic catchment, and x_2, x_3, and x_4 are the ground slopes (%) over distances of 0-15 m, 15-30 m and 30-45 m downwind of the catchment lip. Slopes upward in the direction of the wind are taken as positive, and downward slopes as negative. The upwind part of the drift approaches equilibrium even while the downwind portion remains to be filled in, so that each increment of growth can be calculated considering the portion remaining to be filled as the topographic trap, starting at the cornice.

In general, fences should be aligned perpendicular to the wind direction for maximum efficiency. If the prevailing wind direction is normal to the roadway, the fence is placed parallel to the roadway. If the maximum likely direction of the wind is quartering to the roadway, then short sections of staggered fences should be used. Tabler (1974) recommends fence lengths of at least 30 H and overlaps of 8 H. A number of typical fence layouts for various situations are presented in Pugh and Price (1954), Tabler (1973) and Martinelli (1973).

The storage capacity required for a snow fence system can be estimated for a given prevailing wind and snowfall season if the upwind fetch can be calculated or otherwise determined. The fetch may be determined from topographic considerations, that is, the clear distance upwind to a forest or large snow-trap depression. The amount of vegetation in the upwind area must be known in order to calculate the amount of snow trapped by the vegetation. A theoretical limit to the possible upwind fetch distance exists, because of sublimation of the snow particles, each snow particle will travel a finite distance only before disappearing (Schmidt 1972; Tabler 1975b, 1978).

2.5. Properties of Snow

The physical properties of snow particles (Meller 1964, 1965, 1970; Radok 1968) cover a wide range. Depending upon temperature, the snow can range from very dry (cohesionless powder) to quite wet, where the particles cohere and even freeze together. Listed average sizes of particles range from 0.00236 in. (60 μm) to 0.197 in. (5000 μm), and average terminal speeds are from 7.87 to 102.36 in./sec (20 to 260 cm/sec). However, when blown by strong winds snow crystals are broken and abraded into particles with rounded corners and with size distribution which is roughly monodisperse. Mellor (1970) states that the mean particle diameter is from 0.00276 to 0.00394 in. (70 to 100 microns) higher than 3.94 in. (10 cm) height above the surface. Below 3.94 in. (10 cm) height the mean particle size is larger (0.0065 in. at $z = 1.18$ in., 165 microns at $z = 3$ cm). Since most of the saltating snow is usually in the first inch or two above the surface, the mean diameter is probably between 0.00394 and 0.00591 in. (100 and 150 microns) for blowing snow. The range of particle density is probably from about 0.97 to 1.746 slugs/ft^3 (0.5 to 0.9 gm/cm^3). An average particle, for simulation purposes, is thus selected as a 0.00591 in. (150 micron) diameter sphere, with a density of 1.358 slugs/ft^3 (0.7 gm/cm^3). The threshold friction speed u_{*_t} for this representative particle is 5.47 in./sec (13.9 cm/sec), and the terminal speed U_F is 13.94 in./sec (35.4 cm/sec) at standard sea level. The particle parameter (ratio of terminal to threshold friction speed) is thus $U_F/u_{*_t} = 2.55$. This value is consistent with the observed fact that, except for very strong winds, most or all of the blowing snow stays in the saltation mode rather than going into suspension. The threshold value of wind speed at z = 32.8 ft (10 m) under average snow-covered dry snow conditions on a flat smooth field would be about 7.6 mph (3.4 m/sec), and at z = 6.56 ft (2 m) would be 6.5 mph (2.9 m/sec). This is in the range quoted by Radok (1968) of threshold wind speeds of 4.47 to 8.95 mph (2 to 4 m/sec) at z = 6.56 ft (2 m).

Snow is a very cohesive material. Its hydrologic properties and the fact that the particles, particularly when cold and dry, collect electrostatic charge when blown across the surface cause them to cohere together easily. Part of the ease of cohesion, compared to sand, is because of the low particle density. The angle of repose of sand is 34 deg from the horizontal. The angle of repose of snow can be greater than 90 deg. This large angle of repose capability is the cause of the formation of snow cornices and overhangs.

3. DESIGNING FOR WIND TUNNEL EXPERIMENTATION

The value of wind tunnel testing to determine snowdrift characteristics has been recognized for many years, but relatively few studies have been conducted. Experiments which have been carried out related to highways (or snow fences) include those of Becker (1944), Nokkentved (1940), Norm (1975) in water, and Finney (5). Those related to building proximity include Gerdel and Strom (1961), Strom et al. (1962), Theakston (1970) in water, and de Krasinski and Anson (1975) in water. Experimentally, it is time-consuming and often unrewarding to study snowdrift patterns in the field, since control of weather conditions is not possible and measurements are difficult. Thus, modeling techniques can be very useful if valid predictions can be made from models, since conditions can be carefully controlled and many different situations can be simulated in a short period of time, with much less expense than that incurred with full-scale experiments.

3.1. The Saltation Phenomenon

The movement of loose surface particles by wind is a complex phenomenon. Bagnold's classic work (1941), based on wind tunnel studies and field observations, defines the basic parameters and relations of sand movement by wind. Recent work on threshold* experiments and calculations are reported by Iversen et al. (1976a, 1976b), Sagan and

*The threshold shear stress is defined as that minimum value of stress at which particles begin to move.

Bagnold (1975) for sand, and by Radok (1968 for snow). Much of the early work regarding snow movement has been reviewed by Mellor (1964, 1965, 1970).

The dimensionless threshold friction speed A_1 is given by Bagnold (1941)

$$A_1 = u_{*_t}/(\rho_p g D_p/\rho)^{1/2} \tag{1}$$

For water, ρ_p is replaced by net density $\rho_p - \rho$. Bagnold and most later researchers assumed A_1 was a unique function of particle friction Reynolds number B

$$A_1 = A_1(B),\ B = u_{*_t} D_p/\nu \tag{2}$$

In addition, however, because of the forces of cohesion which particularly affect small particles, it must also be a function of the density ratio ρ/ρ_p (Iversen et al. 1976a, 1976b; Odar 1964). Semi-empirical expressions (Iversen et al. 1976b) have been derived for A_1 as follows

$$A_1 = 0.266 \left(\frac{1 + 3.77(10)^{-6}/\rho_p g D_p^{\,2}}{1 + 2.123B}\right)^{1/2},\ B \leq 0.22$$

$$A_1 = (0.108 + 0.0323/B - 0.00173/B^2) \times \left(1 + 3.77(10)^{-6}/\rho_p g D_p^{\,2}\right)^{1/2},$$
$$0.22 \leq B \leq 10 \tag{3}$$

$$A_1 = 0.11,\ B \geq 10$$

In these equations, the number $3.77(10)^{-6}$ is a dimensional constant of unit slugs sec^{-2} (0.055 gm sec^{-2}). Dimensionless forms of threshold friction speed can be derived as follows:

$$u_{*_t}(\rho/\rho_p g\nu)^{1/3} = (A_1^2 B)^{1/3} \tag{4}$$

$$D_p(\rho_p g/\rho\nu^2)^{1/3} = (B/A_1)^{2/3} \tag{5}$$

A plot of dimensionless threshold friction speed versus dimensionless diameter results in a curve which is concave upward and has a minimum value (for particles of density close to sand at one atmosphere) of approximately 0.28 for dimensionless friction speed at a dimensionless diameter of 3. For particles of lesser density, both numbers are larger, and for greater density, the numbers are smaller because of cohesive forces.

Loose particulate material can move in one of three ways--by creep, saltation, or suspension (Bagnold 1941). Creep is the motion in which large particles do not become airborne but just roll along the surface. Medium size and smaller particles will become airborne as a result of aerodynamic lift or because of a combination of lift and impact from returning particles. The saltating particle rises from the surface in a nearly vertical direction and then gradually returns via a shallow angle trajectory (White et al. 1976, 1977). Very small particles, after becoming airborne, may go into suspension and perhaps rise to great heights before gradually settling out of the atmosphere. The ratio U_f/u_{*_t} (terminal speed to threshold friction speed) is

$$U_f/u_{*_t} = 2/A_1(3\ C_D)^{1/2} \tag{6}$$

where the drag coefficient C_D is a function of Reynolds number

$$C_D = C_D\ (R = U_f\ B/u_{*_t}) \tag{7}$$

$$C_D = 24/R,\ (R \leq 0.1);\ C_D > 24/R,\ (R > 0.1) \tag{8}$$

The mean vertical turbulent eddy velocity in the boundary layer is of the same order of magnitude as the friction speed u_*. Thus, particles which go into suspension do so because their terminal speed U_f is smaller than u_* (or u_{*_t}). An approximate division between dust (material in suspension) and sand (saltating particles) is therefore found by setting the ratio $U_f/u_{*_t} = 1$. For particle diameters large enough so that U_f/u_{*_t} is greater than 1, particles will not become suspended until that ratio u_*/u_{*_t} is reached when U_f/u_* becomes approximately unity. Except for very strong winds, nearly all blowing snow particles move in the saltation mode (Kind 1976). The very small particles for snow do not reach large altitudes as is the case with dust, since the very small particles quickly disappear due to sublimation.

3.2. Modeling of Sediment Transport in Water

While very little simulation of soil, sand, or snow in air has been attempted in wind tunnels, there has been considerable effort for many years in the simulation of sediment transport in rivers, canals and estuaries [ASCE 1942; Warnock 1950]. The modeling of soil and sand movement around model scale obstacles in the wind tunnel has been performed by Woodruff and Zingg (1952) and Iversen et al. (1975, 1976c).

Distorted scales are usually required in those models in water for which horizontal dimensions are much larger than vertical lengths. The vertical scale is increased in relation to the horizontal in order to measure vertical dimensions in the model with relative ease, and to achieve Reynolds numbers high enough to preclude strictly laminar flow.

Since depths and bottom slopes in a water model are increased in a distorted model, the water tends to flow too rapidly, and it is usually necessary to roughen the walls in order to retard the flow. In cases of free surface flows, the Froude number is the parimary similitude parameter which must be satisfied. The vertical length is the appropriate length for scaling by the Froude number, since it determines the relative wave speeds, i.e.,

$$\frac{u_m^2}{h_m g_m} = \frac{u^2}{hg} \tag{9}$$

where h is an appropriate vertical length, u is stream speed, g is gravitational acceleration, and the subscript m indicates model values. The horizontal velocity scale is thus

$$\frac{u_m}{u} = \left(\frac{g_m h_m}{gh}\right)^{1/2} = \frac{x_m}{x}\,\frac{t}{t_m} \tag{10}$$

where x_m/x is the horizontal length scale and t_m/t is the time scale.

$$\frac{t_m}{t} = \frac{x_m}{x}\left(\frac{gh}{g_m h_m}\right)^{1/2} \tag{11}$$

For example, if the horizontal scale is 1/1000 and the vertical is 1/100, the velocity scale is 0.1, and the time scale is 0.01. Thus the flow speed in the model is relatively slow, and time periods are very short.

Introduction of sediment transport into a water model complicates the similitude problem still further. For an undistorted model, the water speed would be so slow and the sediment size so small that material could not be transported. Thus, vertical scale distortion is necessary for sedimentation modeling in water. Satisfying the roughness requirement to provide correct velocity scaling is difficult, however, since the roughness is now a function of the sediment material. These difficulties can be overcome somewhat by careful selection of modeling material (materials of specific gravity lower than sand are usually used). Using a hydraulic flume to model blowing sand or snow in air is not appropriate, because the large disparity in the ratio of fluid to particle density results in a much different saltation trajectory in air than in water.

3.3. Modeling of Sediment Transport in Air

The structure of the turbulent planetary boundary layer has been studied extensively (Haugen 1972). Jensen (1958) and others have observed that the lower portion of the planetary boundary layer (in a neutrally stratified atmosphere) follows the logarithmic law

$$\frac{u(z)}{u_*} = \frac{1}{k} \ln \frac{z}{z_o} \tag{12}$$

as long as the value of the roughness Reynolds number 30 $z_o\ u_*/\nu$ is 70 or greater. The parameter u_* is the friction speed (square root of shear stress divided by air density), and k is von Karman's constant ($k \cong 0.4$). Jensen showed that for simulation of the atmospheric boundary layer, the roughness parameter in the model should be the same as that in the atmosphere, i.e.,

$$\frac{z_{o_m}}{z_o} = \frac{L_m}{L} \tag{13}$$

where L is a characteristic length. Most investigators have relied on the long test section to simulate the turbulent boundary layer profile as a naturally thick, fully turbulent boundary layer (Cermak 1975).

If simple dimensional analysis is used to group the important variables, the following list of similitude parameters, useful in the description of saltation phenomena, can be written.

1. D_p/L particle diameter to length ratio
2. $u(h)/U_f$ reference to particle terminal speed ratio
3. $[u(h)]^2/gL$ Froude number
4. e coefficient of restitution
5. ℓ/L topographic geometric similarity
6. z_o/L roughness similitude
7. z_o'/L roughness similitude in saltation
8. h/L reference height ratio

9. z_o/L^* stability parameter
10. λ/L ripple length ratio
11. U_F/u_{*_t} particle property similitude
12. $u_{*_t} D_p/\nu$ particle friction Reynolds number
13. $u(h) L/\nu$ flow Reynolds number
14. u_*/u_{*_t} friction speed ratio
15. ρ/ρ_p density ratio
16. $u(h)t/L$ time scale

Some of the above parameters are not independent. The roughness height in saltation, z_o', for example, has been assumed by different investigators to be proportional to particle diameter (Zingg 1953), to ripple wave length λ (Bagnold 1941), or to the square of surface friction speed ($z_o' \sim u_*^2/g$) (Owen 1965). Thus, Parameter 7 above would be proportional to Parameter 10, Parameter 1, or to $(3) \times (14)^2/(2)^2 \times (11)^2$.

Consider some of the following modeling parameters.

Froude number: $u(h)^2/gL$

The Froude number can not always be satisfied, since $u_m = u\sqrt{L_m/L}$. If the length scale L/L_m is large, u_m may be too small and the tunnel speed may be below threshold speed. It may also be so low that a minimum Reynolds number requirement might not be satisfied.

Roughness similitude: z_o/L

The aerodynamic roughness should be to scale (Jensen 1958), in order to assure a fully turbulent boundary layer with the appropriate degree of turbulence. If the model must be distorted so that the vertical scale is different from the horizontal scale (see sections on Equivalent

Roughness Height, 2.5.5 and Model Particle Selection, 4.1.2), then the vertical reference length is the appropriate variable, i.e.,

$$\frac{z_{o_m}}{h_m} = \frac{z_o}{h} \tag{14}$$

If the model surface is too smooth to generate the appropriate turbulent boundary layer, then it is necessary to increase z_{o_m} beyond the scaled value in order to try to simulate the correct boundary layer characteristics.

<u>Reynolds number: $u(h)\ L/\nu$</u>

For turbulent flows over sharp-edged features, the flow is relatively independent of the Reynolds number above a given critical value. If the model is too smooth or streamlined in shape so that the test Reynolds number is below critical, the model will have to be distorted by surface roughness, boundary layer trips, sharpened edges, or other factors in order to lower the critical Reynolds number. Snyder (1972) quotes critical Reynolds numbers of 11000 for sharp-edged cubes and 79000 for a hemisphere-cylinder. Each model has its own unique critical Reynolds number, which is somewhat difficult to predict <u>a priori</u>.

<u>Friction speed ratio: u_*/u_{*_t}</u>

The manner in which particles are transported (in particular, the mass rate of movement) is a function of this ratio. Thus, in order to keep u_* as small as possible because of the Froude number, the threshold speed of the particle should be as small as possible.

Reference height ratio: h/L

The reference height h (maximum model height) at which reference speed is measured should be located within the logarithmic portions of the wind tunnel and atmospheric boundary layers.

Particle diameter-length ratio: D_p/L

If the geometric scale L/L_m is large, the necessary particle diameter will be small. Too small a particle is not suitable; cohesive forces create a threshold speed which would not only be too high to satisfy the Froude number, but particles which are too small will go into suspension when blown from the surface and would not simulate a saltation phenomenon. Thus, since it may not be possible to satisfy D_p/L with an undistorted model, vertical distortion in the model may be just as necessary as in sedimentation tests in water.

It is impossible to satisfy all terms of Parameters 1 to 15 simultaneously (Parameter 16 is a prediction term). However, additional aids such as particle equations of motion and theoretical mass transfer rate can be used to group terms and/or determine their importance.

3.4. Review of Snowdrifting Modeling

Finney (1934a, 1937, 1939) and Nokkenvedt (1940) were among the first to attempt to model snowdrifting phenomena in the wind tunnel. Gerdel and Strom (1961) were among the first to consider the laws of similitude in snowdrift modeling. Parameters 1 to 4 of the foregoing list (section 3.3) were suggested by them as those of primary importantce. Odar (1965) and Kind (1976) have also studied the problem in some detail, but have not reported on any experiments. deKrasinski and Anson (1975), Calkins (1975), Theakston (1970), and Norem (1975) have attempted modeling in water. Of these four, only Theakston has not considered the effect of similitude parameters.

The parameters which have been considered important by these investigators are listed in Table 4.

Table 4. Modeling parameters considered by various investigators.

Parameter Number	Gerdel and Strom	deKrasinski and Anson	Odar	Calkins	Norem	Kind
1	X	X			X	
2	X	X		X	X	X
3	X	X	X	X	X	X
4	X	X				
7						X
11				X	X	X
12	X		X	X		
13		X				
14			X	X		
15	X	X	X			
3 × 15			X	X		
3 × 15/1	X	X	X		X	

Obviously, there is some disagreement among these investigators as to which similitude parameters are significant. The most popular is the Froude number, Parameter 3, chosen by all six as an appropriate parameter. That the Froude number, by itself, is not an appropriate parameter is shown by the results of the current investigation.

3.5. Combination of Terms by Theoretical Considerations

Odar (1964, 1965), Iversen et al. (1975, 1976c), and Kind (1976) have used theoretical means, such as the particle equations of motion, in order to determine the most important modeling parameters or possibly to group them and thus reduce the number of variables. In order to write the particle equations of motion, it is first necessary to consider the horizontal air speed within the logarithmic portion of the atmospheric boundary layer (Bagnold 1941):

$$u = \frac{u_*}{0.4} \ln \frac{z}{z_o'} + u' \tag{15}$$

where z is height above the surface of a saltating bed and u' is approximately constant. The value 0.4 represents von Karman's constant, and z_o' is the equivalent roughness height in saltation. A stylized vertical air speed distribution over a topographic obstruction is written as

$$w = w_o - 4w_o x^2/L^2 \tag{16}$$

where w_o is a constant, x is the streamwise distance and L is the horizontal reference length. Let Δu be the relative speed between air and particle,

$$\Delta u = [(u - \dot{x})^2 + (w - \dot{z})^2]^{1/2} \tag{17}$$

where $\dot{x}$ and $\dot{z}$ are the horizontal and vertical components of particle speed. Assuming that the only forces on the particle are aerodynamic drag and weight, the horizontal and vertical equations of motion become

$$\ddot{x} = \frac{3}{4} C_D \frac{\rho \Delta u}{\rho_p D_p} (u - \dot{x}) \tag{18}$$

$$\ddot{z} = \frac{3}{4} C_D \frac{\rho \Delta u}{\rho_p D_p} (w - \dot{z}) - g \tag{19}$$

The following dimensionless variables are defined as

$$\begin{aligned} X &= x/L \\ Z &= z/h \\ U &= u/u_* \\ W &= wL/u_* h \\ T &= t\, u_*/L \end{aligned} \tag{20}$$

where h is the vertical reference height. Equation (17) becomes

$$\Delta u = u_* \left[\left(\frac{1}{0.4} \ln \frac{hZ}{z_o'} + \frac{u'}{u_*} - \frac{dX}{dT}\right)^2 + \left(W_o - 4W_o X^2 - \frac{dZ}{dT}\right)^2 \left(\frac{h}{L}\right)^2\right]^{1/2} \tag{21}$$

For most typical model dimensions, the ratio h/L is small, and therefore, since the vertical air and particle speeds are generally small in comparison to the horizontal components, Eq. (21) can be approximately written as (the second term is of the order of $(h/L)^2$ times the first term)

$$\Delta u \cong u_* \left(\frac{1}{0.4} \ln \frac{hZ}{z_o'} + \frac{u'}{u_*} - \frac{dX}{dT} \right) \tag{22}$$

The equations of motion, Eq. (18) and Eq. (19) become, in dimensionless form,

$$\frac{d^2X}{dT^2} = \frac{3}{4} C_D \frac{\rho L}{\rho_p D_p} \left\{ \frac{1}{0.4} \ln \frac{hZ}{z_o'} + \frac{u'}{u_*} - \frac{dX}{dT} \right\} \left\{ U - \frac{dX}{dT} \right\} \tag{23}$$

$$\frac{d^2Z}{dT^2} = \frac{3}{4} C_D \frac{\rho L}{\rho_p D_p} \left\{ \frac{1}{0.4} \ln \frac{hZ}{z_o'} + \frac{u'}{u_*} - \frac{dX}{dT} \right\} \left\{ W - \frac{dZ}{dT} \right\} - \frac{gL^2}{u_*^2 h} \tag{24}$$

where

$$U - \frac{dX}{dT} = \frac{1}{0.4} \ln \frac{hZ}{z_o'} + \frac{u'}{u_*} - \frac{dX}{dT}$$

$$W - \frac{dZ}{dT} = W_o - 4W_oX^2 - \frac{dZ}{dT} \tag{25}$$

Thus, to ensure dynamic similarity, the dimensionless groups in Eq. (23) and Eq. (24) to be satisfied for correct modeling are

$$\left.\frac{z_o'}{h}\right|_{WT} = \left.\frac{z_o'}{h}\right|_{\text{Full Scale}} \tag{26}$$

$$\left.\frac{x}{L}\right|_{WT} = \left.\frac{x}{L}\right|_{\text{Full Scale}} \tag{27}$$

$$C_D \frac{\rho L}{\rho_p D_p}\bigg|_{WT} = C_D \frac{\rho L}{\rho_p D_p}\bigg|_{\text{Full Scale}} \tag{28}$$

$$\frac{gL^2}{u_*^2 h}\bigg|_{WT} = \frac{gL^2}{u_*^2 h}\bigg|_{\text{Full Scale}} \tag{29}$$

The satisfaction of Eq. (27) is simple, as it merely requires geometric similarity of topographic and gross erosional and depositional features in the horizontal directions. Small-scale bed form features such as ripple wavelengths would not be expected to scale exactly without simultaneous satisfaction of all original modeling parameters, but are probably particularly dependent on the parameters of Eq. (28) and (29).

Odar (1962, 1965) has also considered the dimensionless form of the particle equations of motion. In one case (1965), he defines the dimensionless time as $t(g/L)^{1/2}$ and instead of Eq. (28) and (29) his resulting parameters are $C_D \rho\ u_*^2/\rho_p\ g\ D_p$ and $g\ L/u_*^2$. In the other case (1962), he lists the two parameters gL/u_*^2 and $\rho_p gL/\rho u_*^2$ as the important ones resulting from the particle equations of motion.

3.6. Equivalent Roughness Height

Consideration of the other three similitude equations, Eq. (26), (28) and (29), is somewhat more involved. The equivalent roughness height in saltation, z_o', has not generally been determined. However, Owen (1964) shows that on Earth it is at least approximately proportional to u^{*2}/g, i.e.,

$$z_o' \cong \frac{u_*^2}{2g} \tag{30}$$

Kind (1976) also has considered z_o' to be important in modeling, and, following Owen's results, believes that the Froude number is thus the most important modeling parameter, since (according to Owen)

$$z_o'/L \sim u_*^2/gL$$

Recent calculations of particle trajectories by White et al. (1976, 1977) for various particle densities and for both Earth and Martian atmospheres show that the maximum height in saltation, to which z_o' is probably proportional, involves the ratio of atmospheric to particle density. Thus, an expression more likely to be valid is

$$z_o' \sim \frac{\rho u_*^2}{\rho_p g} \tag{31}$$

The parameter of Eq. (26) thus becomes

$$\frac{z_o'}{h} \sim \frac{\rho u_*^2}{\rho_p gh} = \frac{\rho}{\rho_p g D_p}\left(\frac{u_*}{u_{*_t}}\right)^2 u_{*_t}{}^2 \,\frac{D_p}{h} \tag{32}$$

But $u_{*_t}{}^2 = A_1^2 \rho_p g D_p/\rho$, so Eq. (32) becomes

$$\frac{z_o'}{h} \sim \frac{\rho u_*^2}{\rho_p gh} = A_1^2 \,\frac{D_p}{h}\left(\frac{u_*}{u_{*_t}}\right)^2 \tag{33}$$

Eq. (18) and (19) are particle trajectory equations, and so satisfaction of Eq. (26) through (29) is probably necessary for small-scale eolian bed form features to be properly modeled.

The parameter of Eq. (26) or Eq. (33) is important because of the effect of equivalent roughness in saltation on the turbulence level and mean flow distribution over the model and its wake. Jensen (1958) was the first to recognize the importance of modeling surface roughness correctly when he attempted to simulate the atmospheric boundary layer. Thus, in order to exactly satisfy the equivalent roughness parameter of Eq. (3), it would appear that vertical distortion of the model is required. For example, since Eq. (26) becomes

$$A_1^2 \left(\frac{u_*}{u_{*_t}}\right)^2 \frac{D_p}{h}\Bigg|_{WT} = A_1^2 \left(\frac{u_*}{u_{*_t}}\right)^2 \frac{D_p}{h}\Bigg|_{\text{Full Scale}} \tag{34}$$

and there is a practical lower limit on particle diameter in the wind tunnel, the ratio of h/D_p would be much smaller than in the atmosphere. This equation is not quite as stringent a requirement as the simple ratio D_p/L as mentioned previously, since the ratio $(u_*/u_{*_t})^2$ can be varied and probably will be considerably larger full scale than in the model. The satisfaction of Eq. (34) will not usually be attainable, however, without vertical topographic distortion.

3.7. Transport Rate Similitude

In Iversen et al. (1975, 1976c), experimental correlation of gross erosional and depositional features near model craters was obtained by basing a similitude on rate of mass movement rather than on particle trajectory. The transport rate similitude is based on the theoretical particle mass transport rate. Bagnold (1941) derived the expression for momentum loss of the air due to sand in saltation as

$$\frac{q_s(u_2 - u_1)}{\ell} \cong \frac{q_s u_2}{\ell} = \tau = \rho u_*^2 \tag{35}$$

This quantity represents the momentum loss per unit time per unit length of travel per unit lateral dimension, i.e., momentum loss per unit area per unit time, which is equal to force per unit area or surface stress τ. Mass of sand per unit lateral dimension per unit time is q_s; u_2 is final horizontal velocity on impact; u_1 is initial horizontal velocity, assumed small; ℓ is distance traveled per grain; τ is surface stress; ρ the air density; and u_* the surface friction speed in saltation. Bagnold made the plausible assumption that

$$u_2/\ell \sim g/w_1, \; w_1 \sim u_*$$

so that

$$q_s \sim \frac{\rho u_*^3}{g} \tag{36}$$

A modification of this equation by Iversen et al. (1975), which worked well for a systematic series of raised-rim crater streak simulations, is

$$q_s \sim \frac{\rho}{g} u_*^2 (u_* - u_{*_t}) \tag{37}$$

The rate at which a horizontal area is covered by a drifting material can be expressed as

$$\frac{dA}{dT} = \frac{\text{area}}{\text{mass}} \times \frac{\text{mass}}{\text{time}} \sim \frac{1}{\rho_p h} \times q_s L \tag{38}$$

Similarly, the volume rate is

$$\frac{dV}{dt} \sim q_s L/\rho_p \tag{39}$$

and the cross-sectional area rate (perpendicular to wind direction) is

$$\frac{dA_c}{dt} \sim q_s/\rho_p \tag{40}$$

If these equations are combined with the equation for mass rate of movement, Eq. (37), the following equations result:

$$\frac{d(A/L^2)}{d(u_* t/L)}, \quad \frac{d(V/L^2 h)}{d(u_* t/L)}, \quad \text{or} \quad \frac{d(A_c/Lh)}{d(u_* t/L)} \sim \left(\frac{\rho}{\rho_p}\right)\left(\frac{u_*^2}{gh}\right)\left(1 - \frac{u_{*t}}{u_*}\right) \tag{41}$$

This equation provides a basis for analysis of snowdrifting simulation. The equation combines forms of six of the previously listed similitude parameters (Parameters 3, 5, 11, 14, 15, and 16) from section 3.3. Thus, the similitude problem can be reduced, for example, to the functional relationship (combining Eq. (34), (41), and the Reynolds number requirement):

$$\frac{d(A/L^2)}{d(u_*t/L)} = f\left\{\left(\frac{\rho}{\rho_p}\right)\frac{u_*^2}{gh}\left(1 - \frac{u_{*t}}{u_*}\right),\ A_1^2\left(\frac{u_*}{u_{*t}}\right)^2 \frac{D_p}{h},\ \left(\frac{u_*L}{\nu}\right)\right\} \tag{42}$$

Kind (1976) also briefly considers the mass transport rate in his discussion of modeling. He draws on Owen's (1964) expression for q_s, but does not develop a mass transport rate modeling function as in Eq. (42).

For modeling of gross drifting features, the first term on the right side of Eq. (42) is more important than the second term. If small-scale features (such as surface ripples) are also important, then the second term as well as those of Eq. (28) and (29) must be scaled. Ordinarily, small-scale features such as ripples become important only when the ripple wavelength becomes large enough to significantly affect and/or obscure the gross erosional and depositional features. To systematically model a snow or sand drifting problem, it is desirable to change variables such as the amount of vertical distortion, the particle material, and the wind speed, so that the effect of changes in the values of the dimensionless terms can be evaluated. The use of Eq. (42) to evaluate these changes is necessary, since not all of the original 15 parameters (section 3.3) can be modeled simultaneously.

3.8. Modeling Scale Size Vegetation

This section discusses the selection of materials to be used to model vegetation in the wind tunnel. First, a survey was conducted of other experiments in which plant windbreaks were modeled to determine what types of materials have been used previously. Next, the primary features of the material to be used in these experiments were selected. Finally, various model plant masses were tested in the wind tunnel to find out which created snowdrifts similar to those that could be expected in the field.

The selection of modeling materials for plant masses used in past wind tunnel experiments seems to have been based on an empirical judgment of which materials looked realistic. In his early experiments, Finney (1937) used brush material trimmed to imitate individual trees of a proper height to scale. While this material was of low porosity, increased porosity in the plant mass as a whole could be achieved by manipulating the spacing between trees. The scale for the experiments by Finney was 1 in. = 2 ft. Woodruff and Zingg (1952) constructed a model windbreak out of small cedar branches mounted on a wood block, to the scale of 1 in. = 7.5 ft. In later experiments by the same researchers to the scale of 1 in. = 5 ft, cedar boughs were also used; this time mounted in lengths of 0.25 in. diameter aluminum tubing. This technique was also used by Den Uyl (1936) to model coniferous windbreaks. Woodruff et al. (1963), later developed more precise models for different plant types. Siberian elms were modeled by gluing lichen to small spirea twigs. Models of smaller trees (such as small ash and coffee trees) were constructed of fern and wreath material obtainable from flower shops. Model conifers consisted of lichen supported by florists wire on "trunks" of balsa wood dowels. Nylon burshes whose bristles were heated and bent were used to make models of honeysuckle shrubs in the winter. All of these different types of models were mounted on a styrofoam base.

Three different porosity conditions were simulated in these cases by thinning the model foliage.

The current experiments to study snowdrift control at grade separations were different from the previous experiments listed above in several important respects. The scale being used in all of the above experiments was larger than the 1 in. = 10 ft necessary for tests on the bridge model. The previous experiments were all primarily concerned with measuring the effect of these plant masses on wind velocities and snowdrifting. However, the current experiments involved applications of such information to a particular situation. This necessitated being able to move the model plant mass to different locations on the model.

The essential physical characteristics of a plant mass that needed accurate modeling were determined to be height, width, and porosity. The first two of these could be varied with almost any material chosen. The ability to manipulate the porosity at different levels in the plant mass was also deemed important at the beginning of the investigations. It was also necessary to be able to create a somewhat uniform porosity over the entire length and height of the plant mass.

Since no satisfactory method to measure the porosity of the model plant masses with sufficient accuracy was available, an empirical approach was chosen. This involved not only a visual examination of the model plant masses, but also a wind tunnel test to examine the snowdrifts associated with each plant mass. Model windbreaks were constructed of various materials and with physical characteristics for which general snowdrift shapes could be predicted. Model snow was then blown across the plant masses and the resulting drifts checked against the expectations.

On a 4 ft × 4 ft × 0.25 in. composition board base, with cloth covering identical to that used as a ground cover on the bridge model, nine model plant masses were constructed. These were to the scale of 1 in. = 10 ft and were all 1 in. tall and 1 ft long. Materials included various combinations of balsa wood dowels, twine, cedar twigs, steel wool, lichen, plastic pine branches (called "picks"), wire screen, a plastic floor mat material and a fibrous packing material. Each model and the observations made will be described here separately.

Two models were made to simulate very dense plant masses, one of wire and steel wool and the other of wire and lichen. Using model "trunks" made of twisted wire and "foliage" made of steel wool put down over the top resulted in a windbreak with some gaps in the lower level, although an attempt was made to fill these in. Identical wire "trunks" were also used with lichen for "foliage," with these it seemed easier to fill in the lower level gaps. It was expected that snowdrifting would occur to a distance of about 15 H leeward of these models, with some small amount of drifting windward. This leeward distance turned out to be significantly longer with the wire and lichen model and there was no windward drifting. This indicated that the lower level porosity increased during the wind tunnel tests. The leeward drift associated with the wire and steel wool model was about as expected and maximum snowdrift depth occurred within 2 H leeward. However, there was a large amount of variation in the length, evidence of poor uniformity in the porosity characteristics over the length of the model (see Fig. 27). Due to this uniformity problem (the inability to fill in the lower levels of either model) and the difficulty in moving the models,

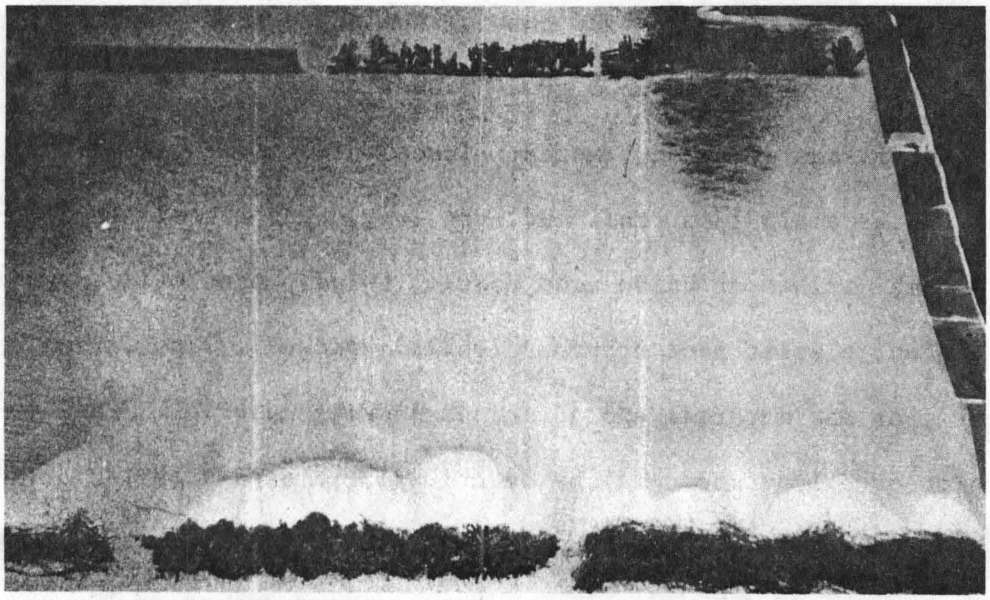

Fig. 27. Wind tunnel tests of various modeling materials. In the foreground are the models made of wire and lichen (left) and wire and steel wool (right). In the background are the models made of screen material (left), cedar twigs (center) and plastic pine picks (right).

neither of these models was satisfactory. (These models were mounted directly on the test board without a separate base for the model. It was felt that a base of sufficient thickness to support the model would also significantly affect drift configuration.)

A more uniform porosity was achieved using steel wool "foliage" placed on "trunks" of 1/16 in. diameter balsa wood dowels mounted 1 in. apart. See Fig. 28 and 29. A medium porosity model was created for all levels and, with a porosity lower than the above two models, a longer drift was expected, perhaps to 27 H leeward, with more drifting windward. However, little windward drifting occurred during wind tunnel testing and the leeward drift was shorter than the models using wire. This last observation might be accounted for by the lack of gaps at the lower level. Although only a small amount of snow was stored, the shape of the drift reflected a uniform porosity.

Two other models at medium porosity windbreaks were made, one of balsa wood dowels and lichen, the other using simulated plastic pine picks mounted 1 in. apart (see Fig. 28 and 29). The first of these models caused snow to drift within the plant mass as may be expected with few low level openings, but there was a wide variation in snow depth and length behind one end of the row compared to the other. Uniform porosity was difficult to achieve. A much more uniform porosity condition was indicated by the drifts associated with the model of plastic pine picks. This model was also simple to construct and it was predicted that various porosity conditions could be simulated by simply varying the spacing. However, very little snow accumulated, even though a uniform medium porosity should create the largest size snowdrift (see Fig. 27). This indicated poor reliability in predicting the porosity of this type of model by visual examination.

Two models with very open porosities were constructed. The first consisted of individual cedar twigs mounted 1 in. apart. Since the foliage on the twigs was of a very fine texture, a uniform porosity along the length of the plant mass was possible, but it was very difficult to fill in the lower levels. Also, the only way to create a windbreak of low porosity from this material would be to make several rows. In testing this model, very little snow was collected and what was collected was deposited in a very irregular snowdrift (see Fig. 27). This

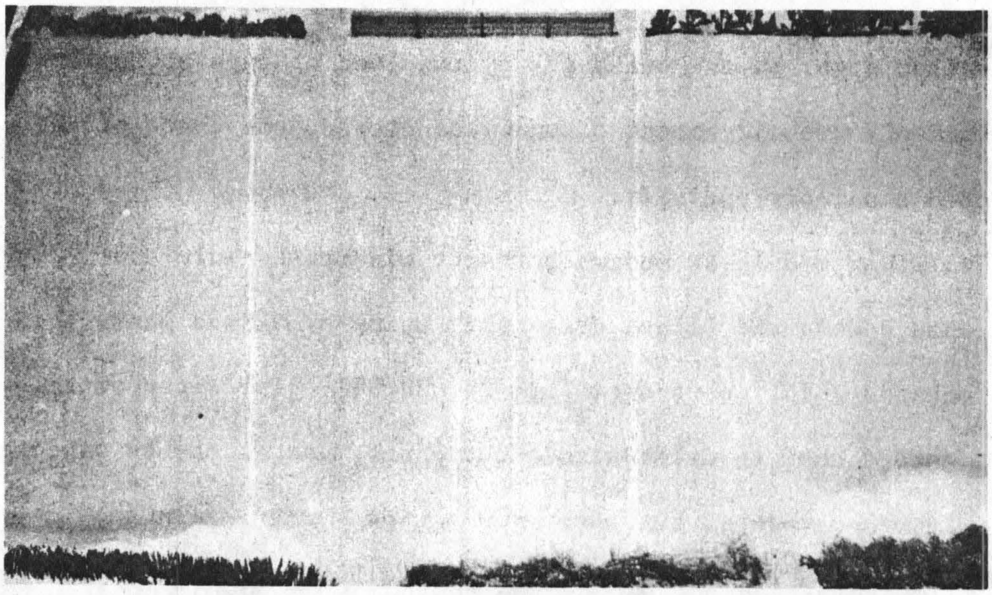

Fig. 28. Wind tunnel tests of various modeling materials. In the foreground can be seen the models made of plastic bristle material (left), dowels and steel wool (center) and wire and lichen (right). In the background are the models of wood dowels and lichen (left), screen material (center), and cedar twigs (right).

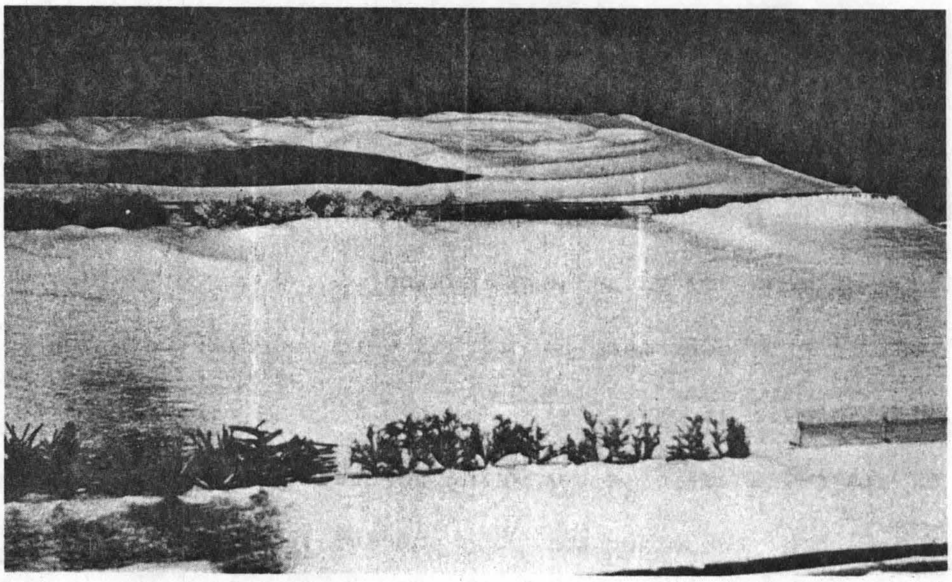

Fig. 29. Wind tunnel test of various modeling materials: in the foreground plastic pine picks (left), cedar twigs (center), screen material (right) and in the background from left to right, wire and steel wool, wire and lichen, wood dowels and steel wool, and plastic bristle material.

model was also much too fragile to be used easily. Another open porosity plant mass model was made of aluminum wire screen (see Fig. 27). This material was chosen because of its excellent mobility and the way in which different porosities could be created by using different size screen meshes. A very small mesh screen cut to 1 in. tall was mounted with wire against balsa wood dowels. This modeling method was abandoned when it was discovered that no snow would drift either leeward or windward.

Two final models were chosen because of their excellent mobility. One was made of a plastic bristle material on a 1/8 in. thick backing, used commercially on rollers for grinding and polishing, and also for floor mats. It was available in many different heights, could be cut to any length and width, could be moved around on its own base, and different porosities could be created by thinning the bristles. A wedge shaped piece 1 in. tall and 1 ft long was cut so as to be wider and less porous at one end, and narrower and more open at the other. The drifting with this model was very realistic. The drift at the wide, solid end began on the windward side, reached its maximum depth within the model plant mass, and ended quickly to the leeward. At the narrow end (very open porosity), the snowdrift began just within the plant mass and then reached its maximum height abruptly at a distance of about 1 H leeward. This drift was long and dropped off very gradually. From this end toward the less porous end, the point of maximum snow depth moved closer to the model, and the overall drift length became shorter, as expected (see Fig. 29).

Another material used was a packing material composed of many loosely interwoven fibers with many air spaces. It was available in 1 in. thick sheets with a net-like backing. It was found that when narrow strips of this material were cut they had a "spongy" quality. When one strip was inverted on top of another (so the net-like backing was both on top and bottom) and compressed somewhat together a lower porosity was achieved. This model plant mass was then fastened to the base with several nails pounded in flush to the top of the plant mass. The porosity was medium to low and uniform throughout the length and height of the model. When tested in the wind tunnel drifting occurred within the plant mass itself and reached its maximum depth within the plant mass. This is very similar to what is expected with a low porosity deciduous shrub (see Fig. 30 and 31). The drift decreased gradually in height from there and did not extend to a great distance leeward. There was a large amount of drifting windward as well. The drift pattern was very uniform, indicating that a uniform porosity was achieved throughout the length of the model plant mass.

This packing material was chosen as the best modeling material for these experiments. It was easy to construct different sized plant masses and move them to different locations on the bridge model, compared to the other materials tested. It also yielded uniform porosities, especially for the low porosities that were needed to control drifting within the small space available within the highway right-of-way, and realistically modeled the very short deciduous plantings that would be necessary in this situation.

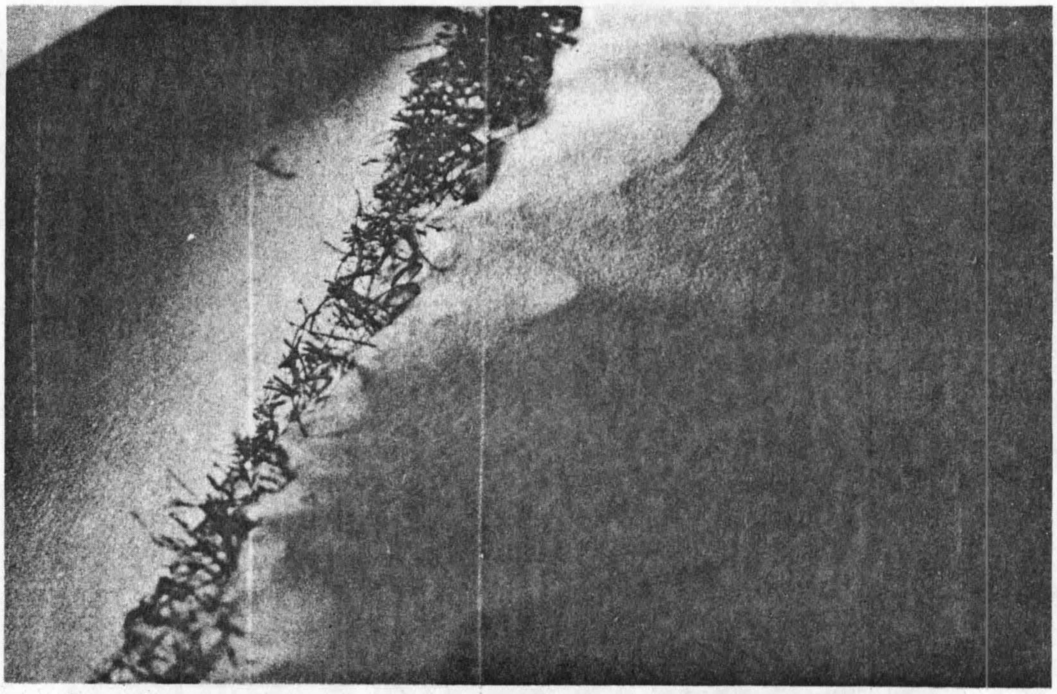

Fig. 30. Wind tunnel test of fibrous packing material showing drifting within and just leeward of the barrier. (Wind moving from left to right.)

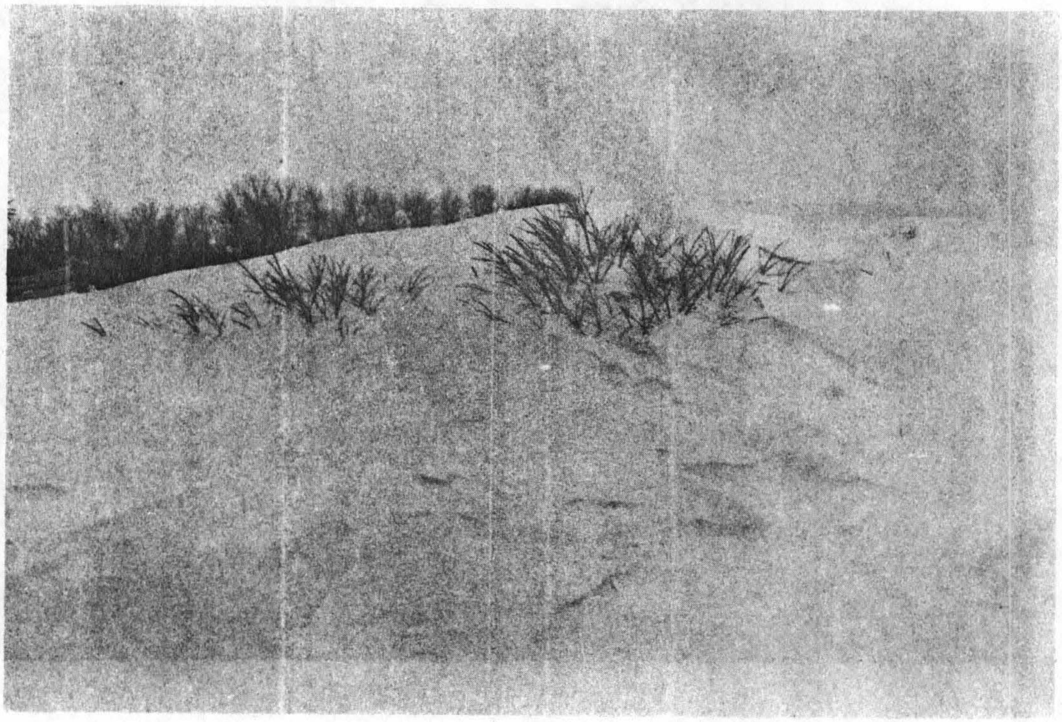

Fig. 31. Snow drifting within and just leeward of low porosity deciduous shrubs.

3.9. Design of the Highway Model

Typical plans for a minor road over-crossing grade separation of a freeway were provided by the Iowa Department of Transportation. The following design criteria is applicable for the base model design (a typical plan view is included as Fig. 32).

Freeway

- two 24 ft pavements
- 10 ft shoulders on right
- 6 ft shoulders on left
- 50 ft median (between pavement edges)
- 6:1 foreslopes
- 4 span bridge, pier centered in median
- 35-90-90-35 ft normal bridge spans
- 30 ft clearance from pavement to right hand pier
- 2.5 ft diameter piers (three columns)
- 3 ft deep right hand ditch
- 10 ft wide ditch bottom
- 1:2.5 slope berm under bridge

Minor Road

- 3:1 side slopes
- 44 ft roadway
- 10 ft wide road ditch
- 3 ft deep minor road ditch

The basic model represents a typical grade separation at a minor road crossing on a flat landscape. It is recognized that in many cases

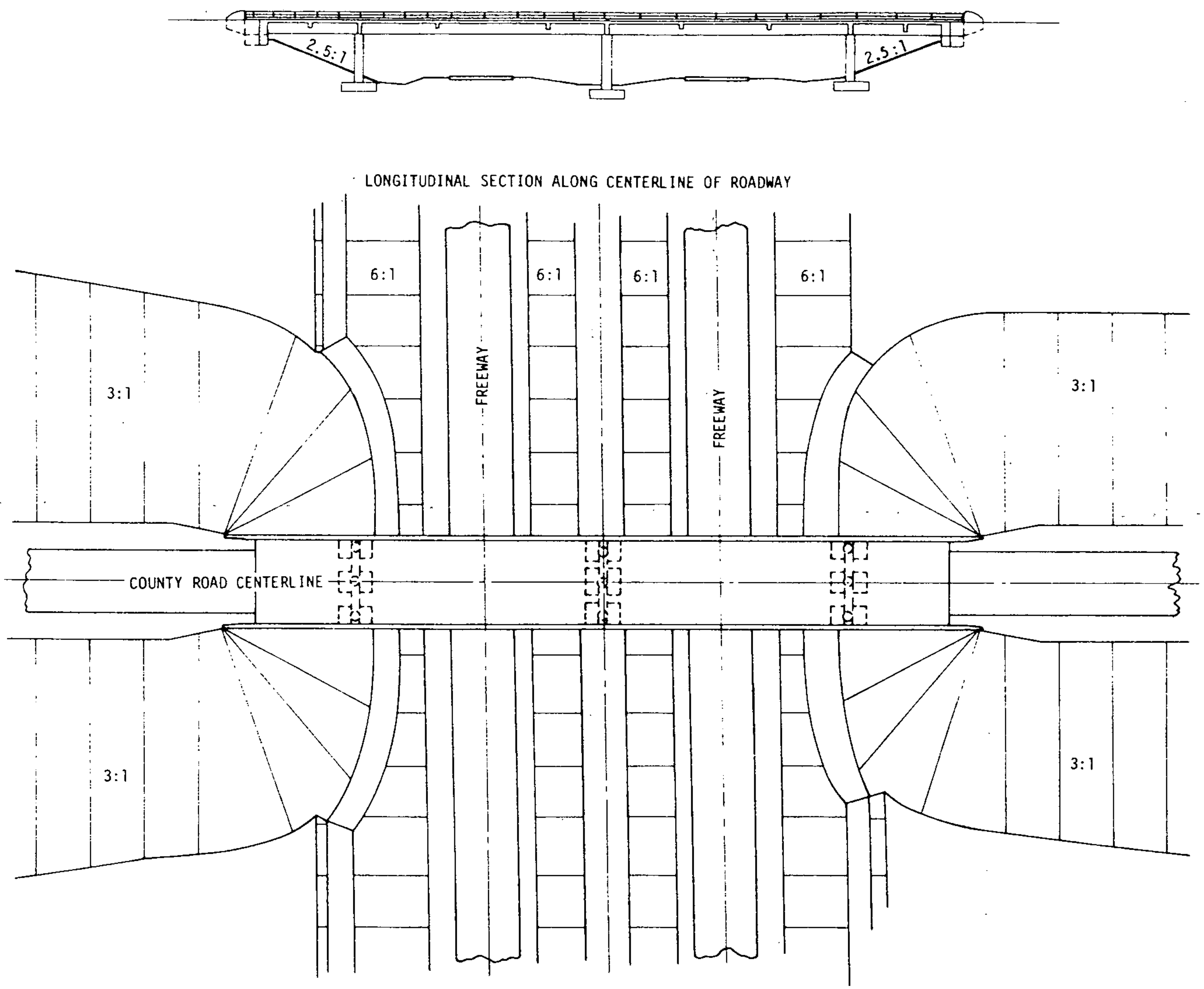

Fig. 32. Situation plan (not to scale).

rolling topography, adjacent farmsteads, groves of trees and other non-typical conditions influence the drift patterns of the snow. It is, however, beyond the capability of this particular research project to investigate all these situations. A basic study of wind blown snow phenomena will provide aid in applications to non-typical conditions.

The Iowa State University wind tunnel has a 4 ft width for model testing, limiting the scale of experiments. Also, it was determined that the model would require a simulation of approximately 230 ft of approach area, 280 ft of bridge, and 90 ft of downwind embankment, or a total length of approximately 600 ft. In order to achieve a rotation of 45 deg, to simulate different angles of wind incidence, the corners were rounded and a small portion of the downwind model was made removable.

After preliminary investigation it was decided to construct the following two models at a horizontal scale of 1:120.

- Model No. 1: 1 in. = 10 ft horizontal and 1 in. = 10 ft vertical
- Model No. 2: 1 in. = 10 ft horizontal and 1 in. = 5 ft vertical

The embankments were of cedar wood shaped to the desired cross section. The bridge was constructed of plexiglas and the piers were aluminum. The roadways were plexiglas to simulate smooth pavement, and the shoulders were fine sandpaper. The freeway cross section was machined from a plywood panel and the sideroad embankments and bridge attached to this base. Figure 33 shows two views of the model. When placed in the wind tunnel, the adjacent space was filled with wood panels to assure a smooth transition to the landscape.

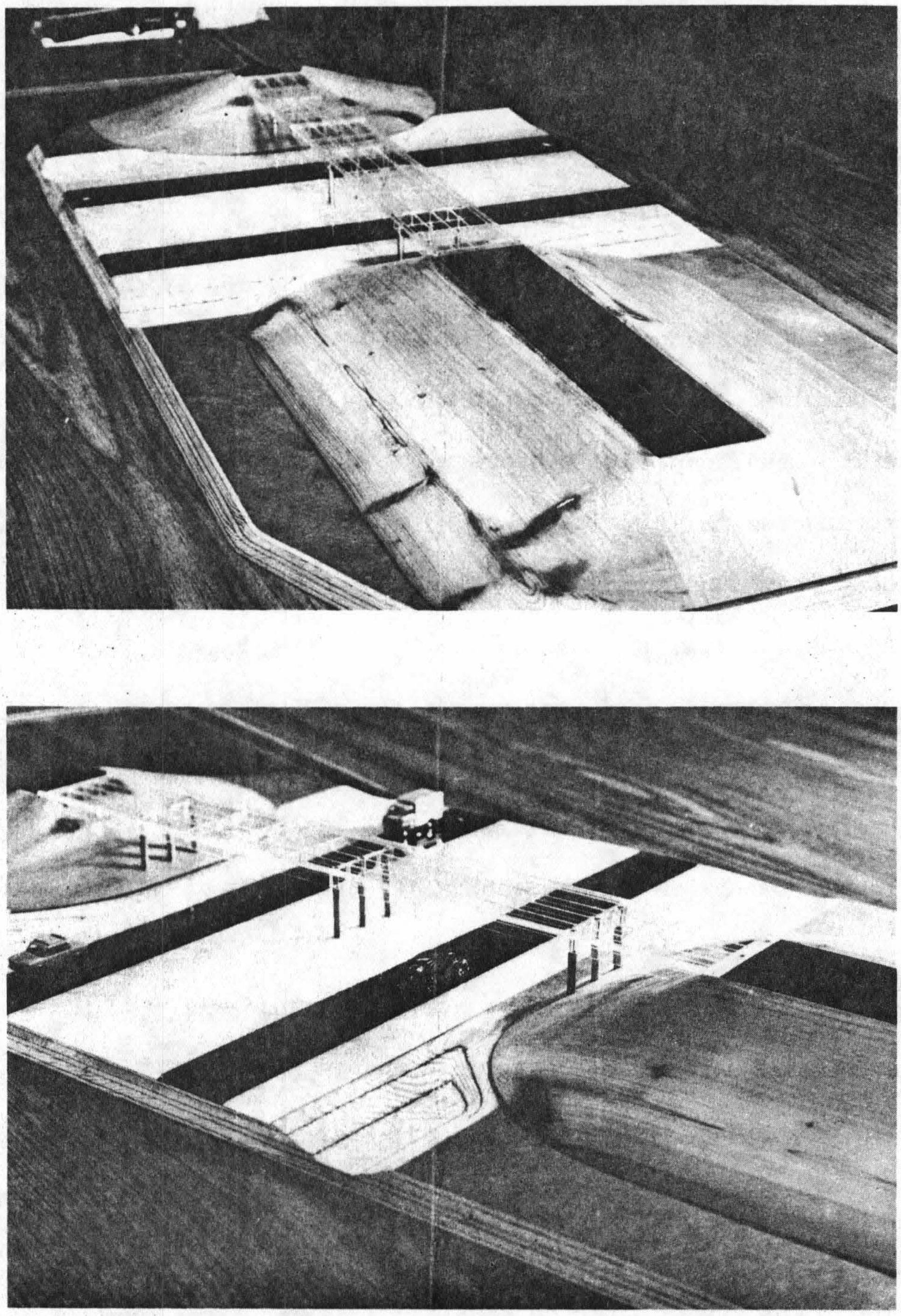

Fig. 33. Views of the bare model prior to testing.

Preliminary experiments in the wind tunnel on the bare surfaces were not satisfactory. "Snow" would simply not accumulate on the smooth landscape. Iowa does not mow the entire right of way, and unmowed ground cover generally stands up to 2 ft and has approximately a 90% porosity. After numerous experiments on a flat panel, the model was covered with a low nap velour material to simulate ground cover.

For Model No. 2 a longer nap ground cover cloth material was selected for the distorted vertical scale.

4. WIND TUNNEL EXPERIMENTATION

4.1. Procedure for Simulating Snow Storms in the Wind Tunnel

4.1.1. The Modeling Parameters

The four similitude parameters from section 3.0 are as follows:

1. $C_D \rho L/\rho_p D_p$ (Terminal Speed Parameter, from Eq. (28))

2. $gL^2/u_*^2 h$ (Froude Number, from Eq. (29))

3. $A_1^2 \frac{D_p}{h}\left(\frac{u_*}{u_{*_t}}\right)^2$ (Equivalent Roughness, from Eq. (34))

4. $\frac{d(A/L^2)}{d(u_* t/L)} \Bigg/ \left\{\left(\frac{\rho}{\rho_p}\right)\left(\frac{u_*^2}{gh}\right)\left(1 - \frac{u_{*_t}}{u_*}\right)\right\}$ (Mass Rate Parameter from Eq. (41))

In addition to these parameters having to do with particle motion, the usual atmospheric boundary layer parameters related to geometry and viscosity must be considered (ℓ/L, z_o/L, h/L, z_o/L^*, $u(h)\, L/\nu$).

From past experience (Iversen et al. 1975, 1976c), for modeling of drift features, Parameter 4,* appears to be the most important of the saltation parameters. Parameter 3 is somewhat less important, and generally speaking, Parameters 1 and 2 are important only if small-scale features (such as surface ripples) affect the larger scale drift patterns. The quantity A/L^2 (planform drift area) can be replaced by V/L^2h (drift volume) or A_c/Lh (drift profile area). To systematically model a snow or sand drifting problem, it is desirable to change variables such as the amount of vertical distortion (to ascertain the effect of Parameter 3), particle material, and wind speed, so that the effect of changes in the

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*All parameters mentioned in section 4.0 refer to those listed at the beginning of section 4.1.1. unless otherwise indicated.

values of the dimensionless terms can be evaluated. The use of Parameters 3 and 4 to evaluate these changes is necessary, since not all of the original 15 parameters (section 3.3.) can be modeled simultaneously.

4.1.2. Model Particle Selection

Figure 34 illustrates an approach to particle selection. Curves of constant $C_D\rho/\rho_p D_p$ (Parameter 1), constant $A^2 D_p$ (Parameter 3) and constant U_F/u_{*_t} are shown in Fig. 34. First, it is necessary to select materials that lie to the right of the barred curve ($U_F/u_{*_t} = 1$), so that the primary transport mode is saltation. (Blowing snow occurs primarily in the saltation mode rather than suspension, perhaps because very small particles disappear quickly due to sublimation.) Conflicting requirements exist for a small scale model. In order to satisfy Parameter 2, it is necessary to pick a particle of less density than snow. To satisfy Parameter 1, a smaller particle must be chosen. Finally, to satisfy Parameter 3, a larger density is required. Five materials were selected for trial for the highway-grade separation experiments (model scale 1:120). Their properties and modeling parameter values are listed in Table 5.

The last three columns of the table list the values of the modeling Parameters 1, 2, and 3, respectively. Particle No. 4 is closest to the terminal speed-threshold speed ratio; Particle No. 2 comes closest to satisfying Parameter 1; Particle No. 1 is nearest the value of Parameter 2 for snow at full scale; and Particle No. 5 comes closest to satisfying the roughness Parameter 3. After testing the five particles, No. 1 and 2 were immediately ruled out; No. 1 because the roughness parameter was much too large (in addition to difficulty in working with the material) and No. 2 because most of the material becomes suspended rather than

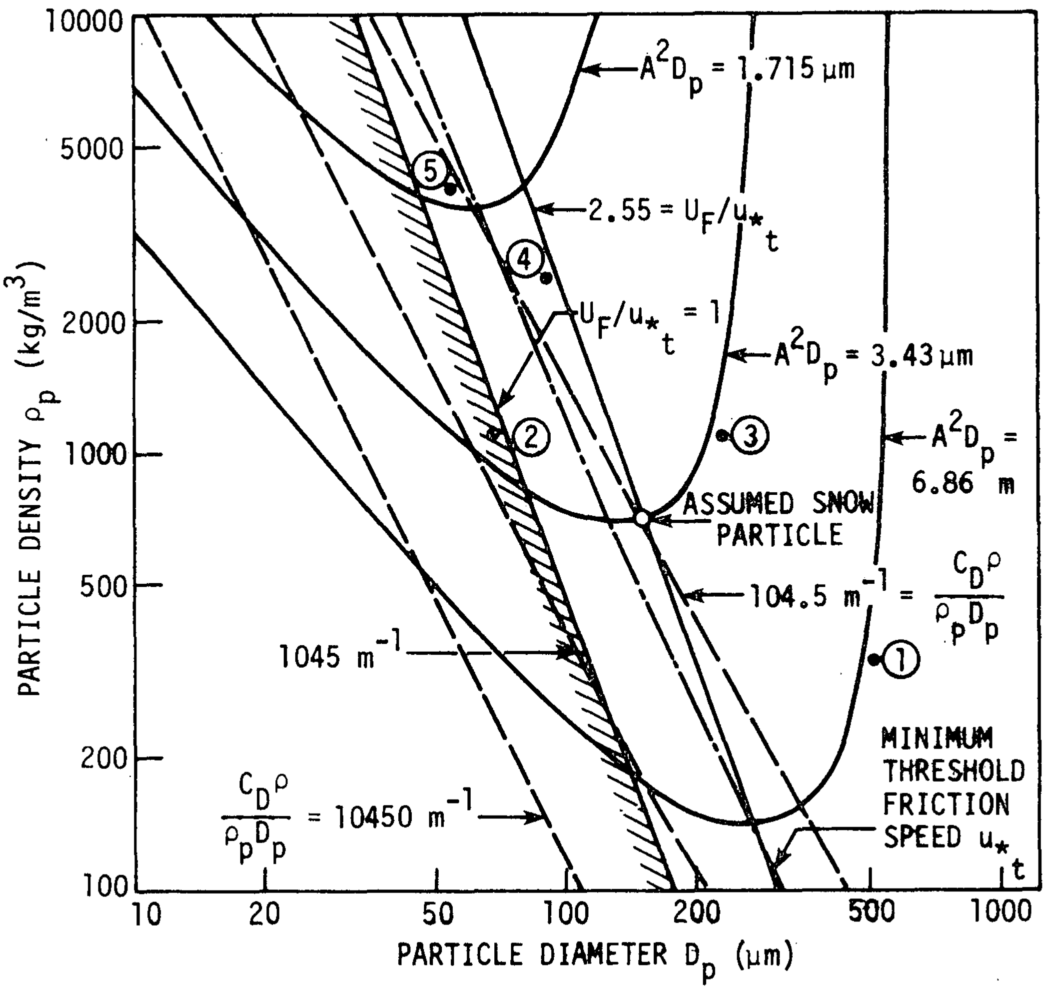


Fig. 34. Variation of similitude values with particle density and diameter. Circled numbers refer to the modeling particles listed in Table 5.

moving in the saltation mode since $U_F/u_{*_t} < 1$. The latter three materials are all fairly satisfactory. Number 5, the dense glass sphere, was used for the majority of testing for three reasons. First, the most important of the first three parameters, the roughness parameter, comes closest to the full scale value. Second, because of the small size of these particles and resultant cohesive properties, the angle of repose during drift formation can be significantly higher than the large particle value of 34 deg (close to 60 or 70 deg, probably primarily because of

Table 5. Materials selected for trial for highway-grade separation experiments.

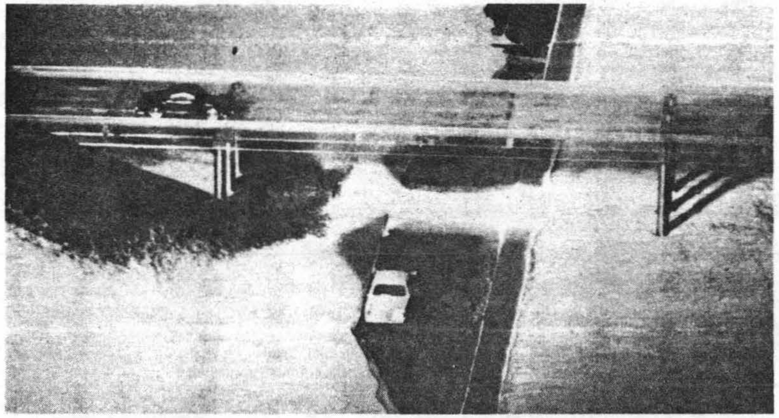
Model Particle	Particle Properties and Parametric Values					
	Density gm/cm^3	Diameter μm	U_F/u_{*t}	$C_D \rho L/\rho_p D_p$	$gL^2/u_{*t}^2 h$	$A_1^2 D_p U^2/U_o^2 h$ (typical)
1. Instant tea	0.2	500	6	3.3	10,000	$3.2(10)^{-3}$
2. Walnut shell	1.1	69	0.9	400	4,000	$8.9(10)^{-4}$
3. Walnut shell	1.1	268	5.96	7.5	3,600	$7.0(10)^{-4}$
4. Glass spheres	2.5	101	2.8	28.0	3,000	$4.4(10)^{-4}$
5. Glass spheres	4.0	49	1.3	125	2,600	$2.5(10)^{-4}$
6. Snow (full scale)	0.7	150	2.55	900	750,000	7.2(10)-5

electrostatic charge accumulated because of particle movement) and thus drifts can form (including the formation of cornices) that more closely resemble full-scale snowdrifts. Third, with the large particle density, it is easier to obtain predicted realistic values of full-scale wind speed (from the mass-rate parameter). The five particles are identified by the numbered dots in Fig. 34.

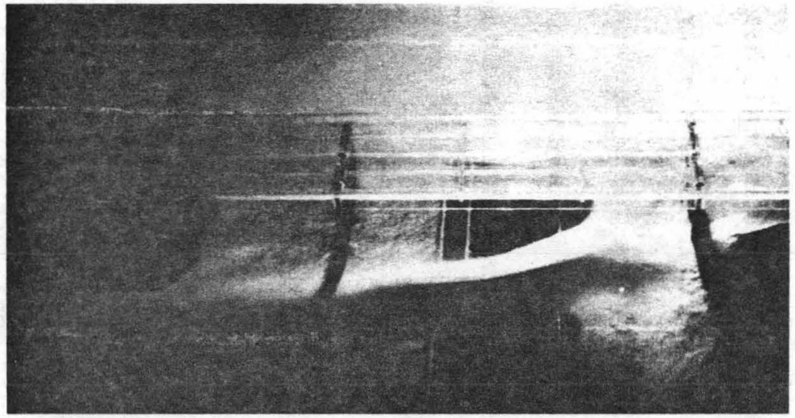
4.2. Mass-Rate Parameter Correlation

Both the undistorted and vertically distorted grade separation models were tested without drift-control simulated vegetation, not only in order to compare with control planting configurations but also to obtain appropriate similitude relationships for more exact configuration comparisons and for possible extrapolation to full-scale. Photographs of these experiments with the wind direction parallel to the bridge and at angles of 20 deg and 40 deg to the bridge centerline are shown in Fig. 35. With the wind direction parallel to the bridge centerline, a total of 13 bare (simulated grass only) model experiments were analyzed to produce the relationship desired. Ten of these experiments were with the undistorted model and three with the distorted model. Two experiments were with the 268 micron shell particle (No. 3), three were with the 101 micron light glass (No. 4) and the other eight were with the 49 micron dense glass (No. 5). The 49 micron dense glass was used for all the remaining drift-control experiments.

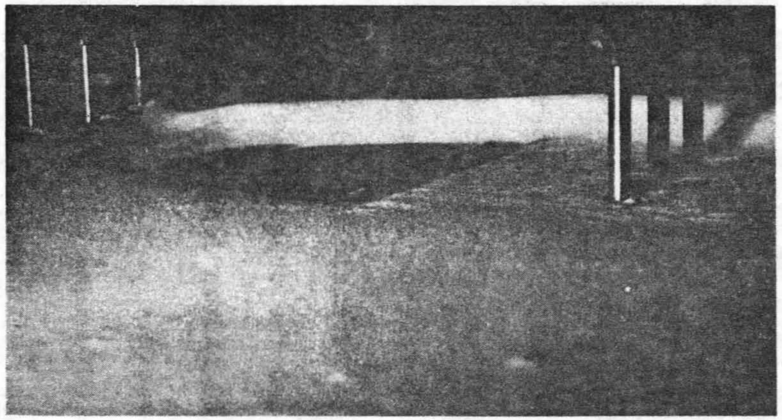
The range of values of the four modeling parameters in the 13 bare model tests along with the corresponding full-scale values are shown in



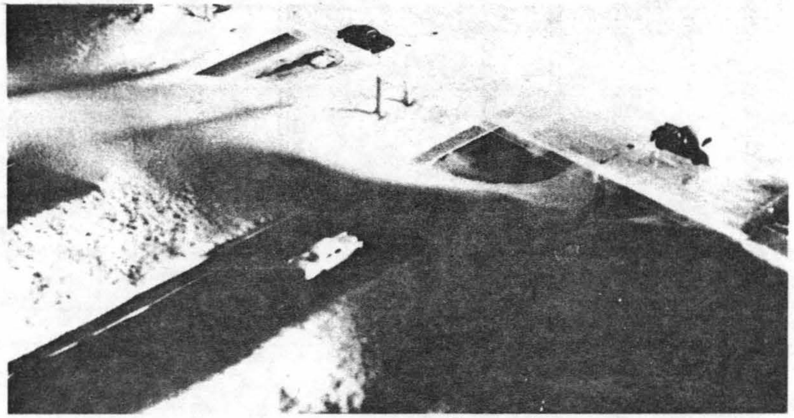
Bare model test: 0° wind direction left to right (10-14-1).



Bare model test: 20° wind direction right to left (12-7-1).



Bare model test: 20° wind direction left to right (12-7-1).



Bare model test: 40° wind direction right to left (2-24-1).

Fig. 35. Photographs of bare Model 1 (simulated grass only) experiments. Wind tunnel tests at 0, 20, and 40 deg wind directions.

Table 6. The values of area A correspond to the snowdrift area (in plan) covering a 42 in. length of both lanes of highway including the shoulders. Obviously, the first two parameters are not modeled. These two parameters are of primary importance only if small scale surface forms, such as ripples, are to be modeled to scale. Because of the use of the distorted model, the values of the third and fourth parameters, namely the roughness and mass rate parameters, do overlap the corresponding full-scale values; thereby lending more confidence in the results of the scale model tests, since the third and fourth parameters are by far the most important in determining the gross drifting features and drift accumulation rate.

The center of the bridge of the 1:120 scale model was placed 5 m downwind of the entrance to the Iowa State University Environmental Wind Tunnel test section. The wind tunnel test section is 1.2 m by 1.2 m in cross section. Turbulence generating spires were placed at the test section entrance to increase the logarithmic portion of the boundary layer to a depth of 25 cm (Model 1 height was 5.84 cm and Model 2, 11.68 cm).* Model 1 was covered (except for the road lanes) with velour fabric to simulate a grassy surface. A thicker fabric was used for Model 2 to obtain simulated grass approximately twice as tall.

Modeling particle material was placed to a uniform depth of 1.5 cm (3 cm for Model 2) across the test section width from 2.3 m to 3.7 m downwind of the test section entrance prior to the start of each experiment. Plan view photographs of the model during the experiment were taken at recorded times during each test run. Typical photographic

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*See section 3.9 for a description of the two 1:120 scale models.

Table 6. Values of modeling parameters from calibration tests.

Parameter	Range of Model Values				Range of Full Scale Values
	Shell	Light Glass	Dense Glass	Distorted with Dense Glass	
$C_D \rho L/\rho_p D_p$	7.6 to 7.7	28.1 to 28.7	113 to 125	115 to 117	27,000
gL^2/U^2h	4.4 to 5.0	2.9 to 4.0	2.7 to 6.8	1.6 to 2.3	21 to 76
$A_1^2 \frac{D_p}{h}\left(\frac{u_*}{u_{*_t}}\right)^2$	$7.1(10)^{-4}$ to $7.8(10)^{-4}$	$3.8(10)^{-4}$ to $5.2(10)^{-4}$	$1.5(10)^{-4}$ to $3.5(10)^{-4}$	$9.5(10)^{-5}$ to $1.3(10)^{-4}$	$3.0(10)^{-5}$ to $1.1(10)^{-4}$
$\dfrac{\dfrac{d(A/L^2)}{d(Ut/L)}}{\left\{\dfrac{\rho}{\rho_p}\dfrac{U^2}{2gh}\left(1 - \dfrac{U_o}{U_\infty}\right)\right\}}$	0.0019 to 0.0020	0.0024 to 0.0029	0.0025 to 0.0037	0.0045 to 0.0050	0.004 to 0.008

sequences are shown in the Supplement.* The amount of planform drift area on both upwind and downwind lanes was measured by planimeter from drawings constructed from negative projections. The total drift area as a function of time with the dense glass particle is shown in Fig. 36 for five different wind speeds, with wind direction parallel to the bridge. The data illustrated in this figure were used to extrapolate the results to zero movement of material, using Parameter 4 as an extrapolation equation to obtain a threshold wind speed. Without the Similitude Parameter 4, the only time-dependent correlation parameter would be Parameter 16 (see section 3.3). That this parameter is not satisfactory by itself as a correlation or prediction parameter is illustrated by Fig. 36, which shows drift area as a function of $U_\infty \Delta t/L$. Figure 37 illustrates the utility of the mass rate similitude Parameter 4. Data from four of the five runs is well correlated by this parameter. The curve for the highest speed run does not correlate partly because of the fact that the ratio of U_F/u_{*_t} for this material is very close to 1, and for this high wind speed, a significant amount escapes the saltation mode, and goes into suspension, and therefore is not available for drift formation on the highway lanes. As shown in section 4.3., the reason for incomplete correlation is also due to changes in the equivalent roughness ratio parameter.

*Wind Tunnel Analysis of the Effects of Plantings at Highway Grade Separation Structures: Supplement, Engineering Research Institute, Iowa State University, Ames, Iowa, June 1979.

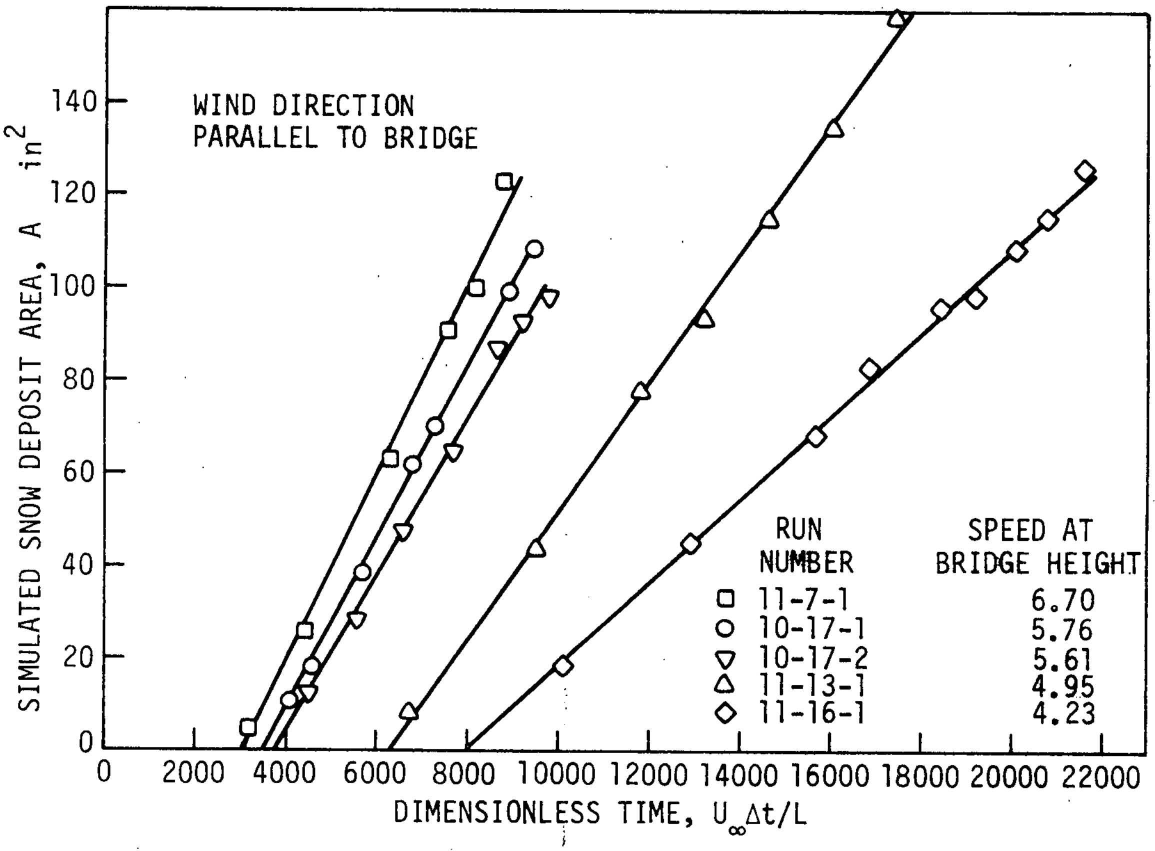


Fig. 36. Accumulated simulated snowdrift plan area as a function of dimensionless time; determined from photographs for five different wind speeds. Wind direction parallel to bridge for bare model. Speed in m/sec.

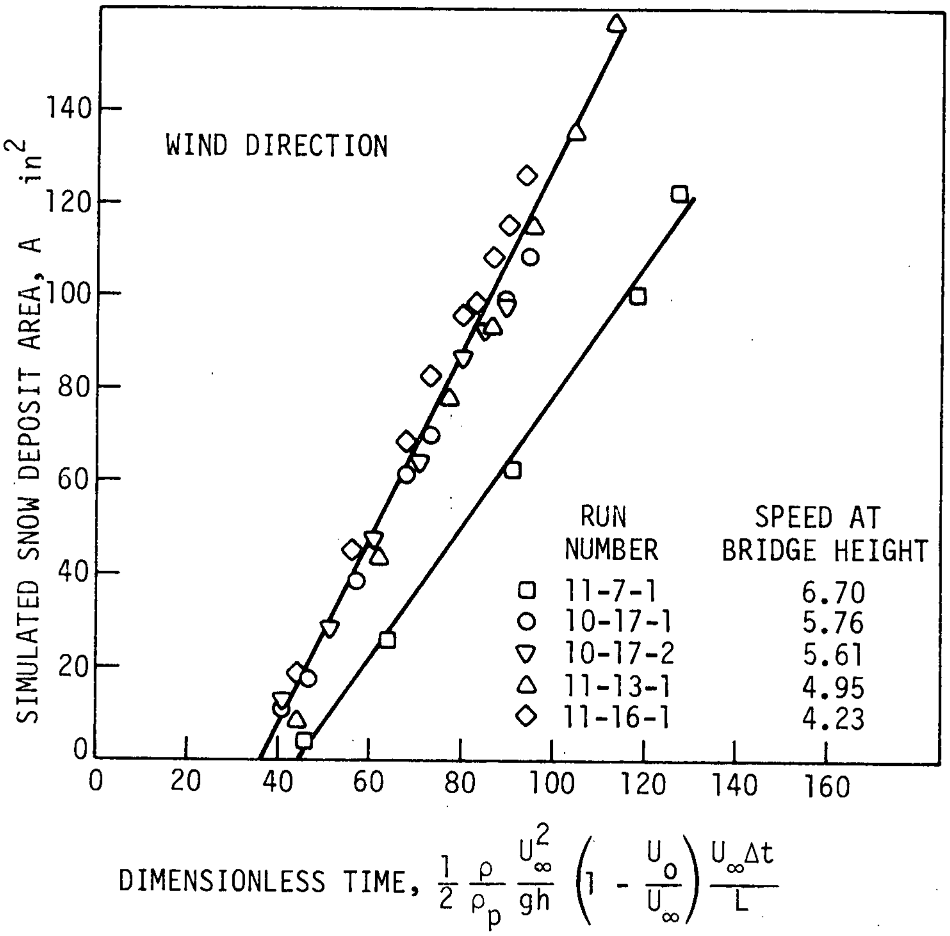


Fig. 37. Drift plan area accumulation of simulated snow as a function of dimensionless time using mass-rate parameter. Wind direction parallel to bridge for bare model. Speed in m/s.

4.3. Effect of Saltation Roughness

The effect of the equivalent roughness height in saltation is more subtle than the effect of the mass rate parameter, but is still significant. A wide range of values of the equivalent roughness parameter was obtained by using modeling materials of different density and diameter, by varying the values of wind tunnel speed, and by testing Model 2, the geometrically distorted model. The ratio of maximum to minimum value of roughness achieved in this manner was 5.39 without the distorted model, and 8.24 with the additional testing of Model 2. The variation of the mass rate parameter with the roughness parameter is illustrated in Fig. 38. Linear regression was used to fit a power law curve to the data, resulting in the equation:

$$\frac{(\Delta A/L^2)}{\left\{\frac{1}{2}\frac{\rho}{\rho_p}\frac{U_\infty^2}{gh}\left(1-\frac{U_o}{U_\infty}\right)\frac{U_\infty \Delta t}{L}\right\}} = 6.525(10)^{-5}\left\{A_1^2\,\frac{D_p}{h}\left(\frac{U_\infty}{U_o}\right)^2\right\}^{-0.43128} \tag{43}$$

The correlation coefficient for this fit is $R = -0.966$ (a perfect fit results in $R = \pm 1$; if no correlation exists, $R = 0$). As equivalent roughness increases, the dimensionless mass rate of motion decreases, which is what one would intuitively expect.

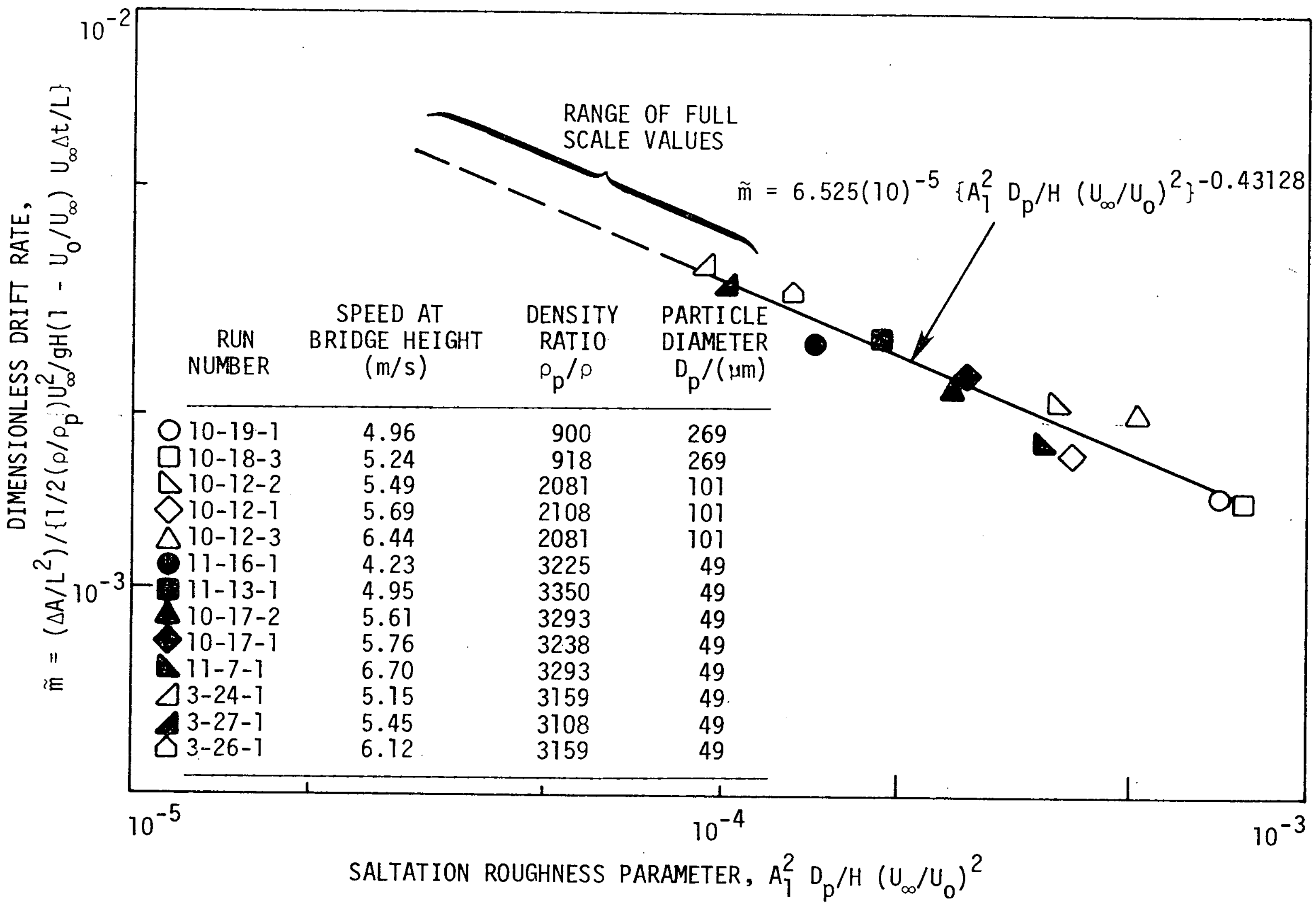


Fig. 38. Dimensionless plan area drift rate incorporating the mass-rate parameter versus the saltation roughness parameter. Data are for 0 deg wind direction, three different snow simulation particles, and a variety of wind speeds. Uncontrolled (bare) Model 1.

The exponent in Eq. (43) is close to -3/7 in value. A plot of dimensionless area rate $(\Delta A/L^2)/(U_\infty \Delta t/L)$ is plotted versus a modified Froude number-roughness parameter in Fig. 39. For this curve, the correlation coefficient is 0.983. The utility of the mass-rate roughness parameter in correlating the model calibration data is shown in Fig. 40 and 41. The dimensionless area A/L^2 is plotted versus dimensionless time $U_\infty(t - t_o)/L$ in Fig. 40, where t_o is the intercept of the straight line portion of the curve for each run. The data are rather successfully collapsed into a single curve in Fig. 41, with a correlation coefficient R = 0.992.

The next three figures illustrate the differences between attempting to correlate using the Froude number, which most authors have used as the primary similitude parameter, and other parameters which incorporate the fluid to particle density ratio. Fig. 42 shows $\Delta(A/L^2)/(U_\infty \Delta t/L)$ as a function of Froude number U_∞^2/gh. The correlation is obviously not good and the correlation coefficient R is only = 0.706. A considerable improvement is obtained by using a type of Richardson number as in Fig. 43. This is equivalent to using Bagnold's expression (1941) for the mass-rate equation. Calkins (1975) indicated that this is an appropriate similitude parameter for drifting snow, although he did not indicate why he thought so. Calkins went on to abandon this parameter, however, because he was using a water flume for simulation and the basic Froude number gives a much more realistic full scale value for wind speed in that case than does the Richardson number. The correlation coefficient in Fig. 43 is 0.956. A Richardson-type number derived from the mass-rate equation, Eq. (41), is used for correlation in Fig. 44. The correlation improves

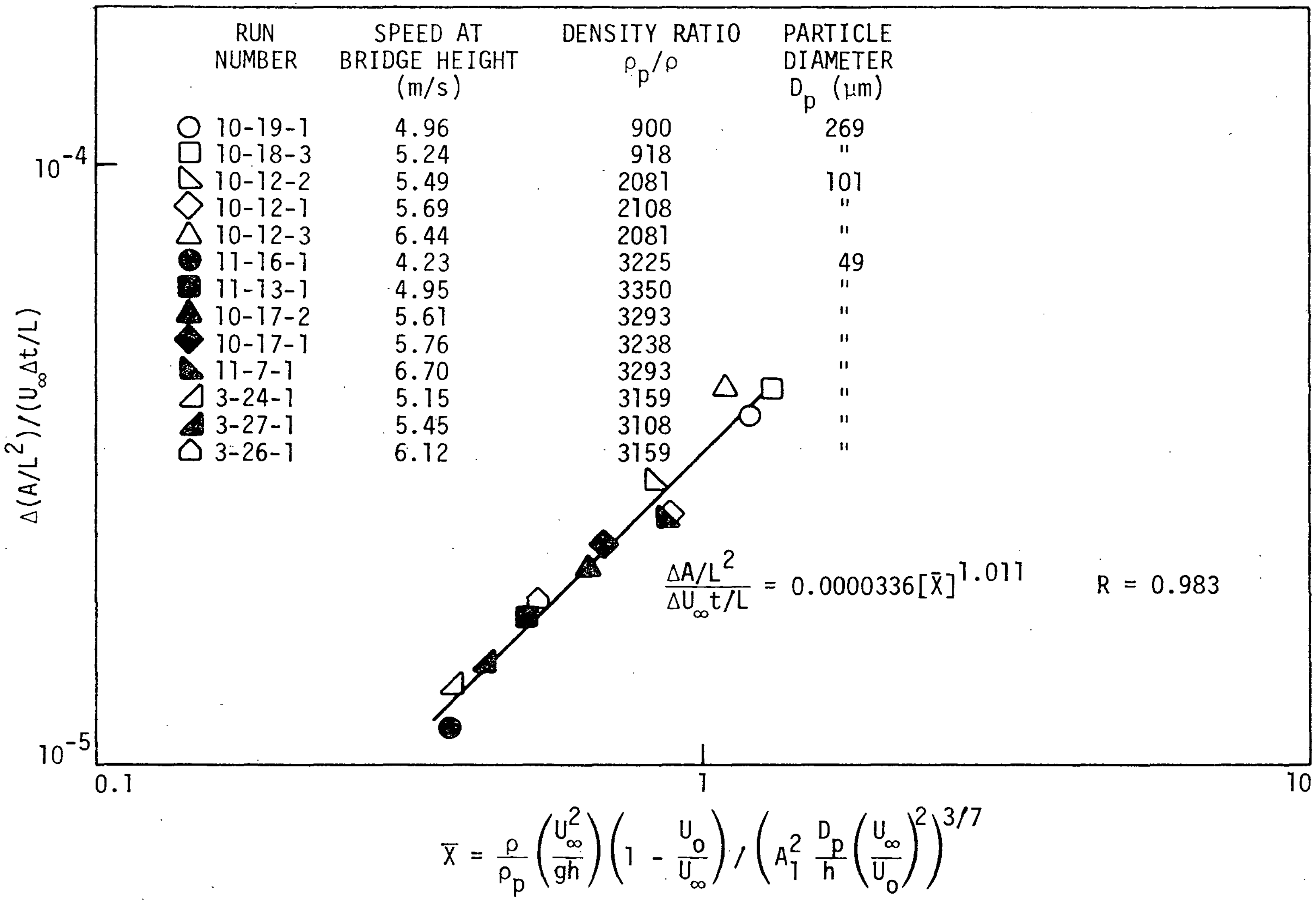


Fig. 39. Plan area drift rate at 0 deg wind direction (bare model) as a function of combined mass rate - roughness parameter. Correlation coefficient R = 0.983.

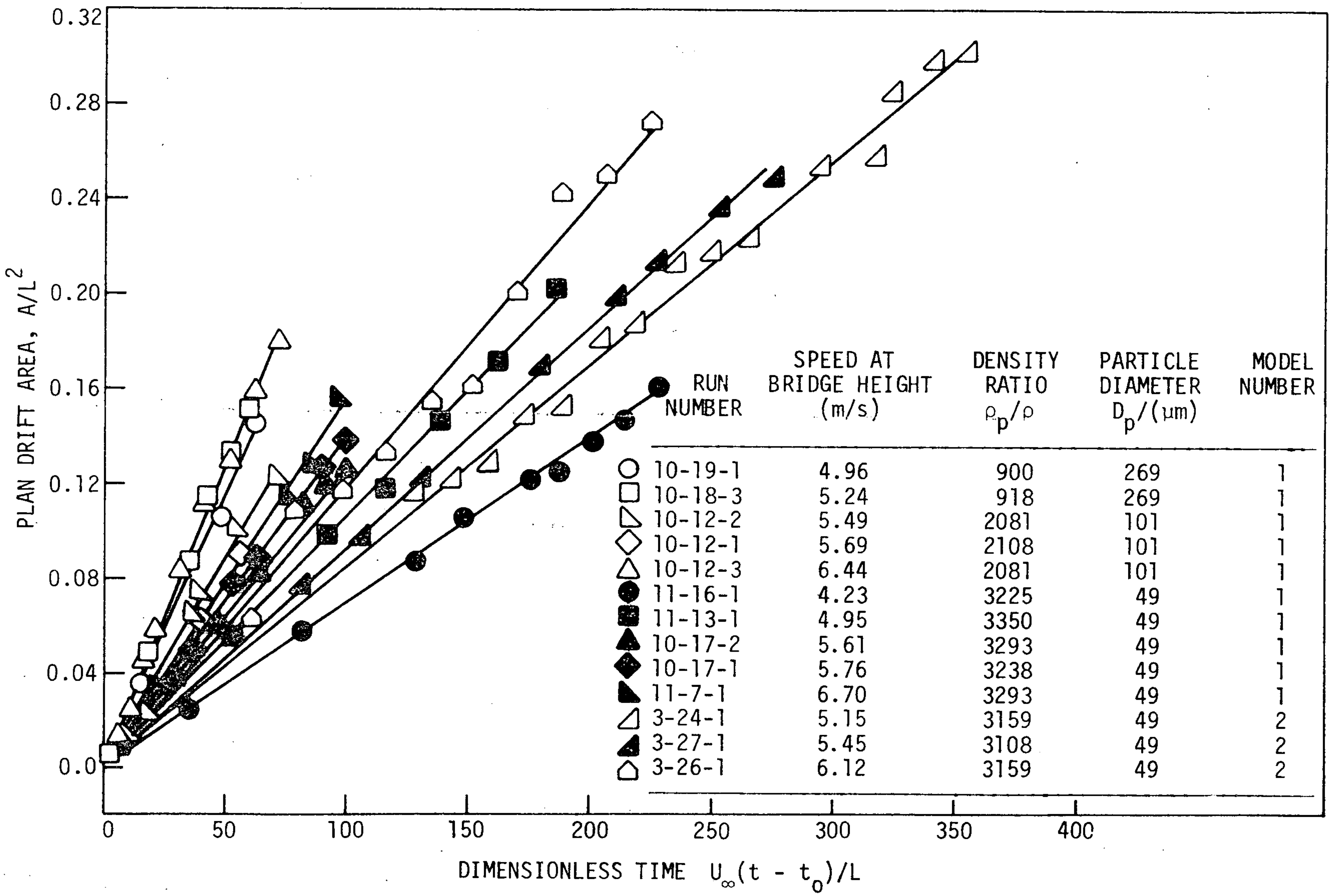


Fig. 40. Drift plan area accumulation of simulated snow as a function of dimensionless time. Data are for 0 deg wind direction for bare Model 1. Speed ranges from 4.23 m/sec to 6.70 m/sec, particle density from 1100 to 3990 kg/m^3 and particle diameter from 49 to 269 μm.

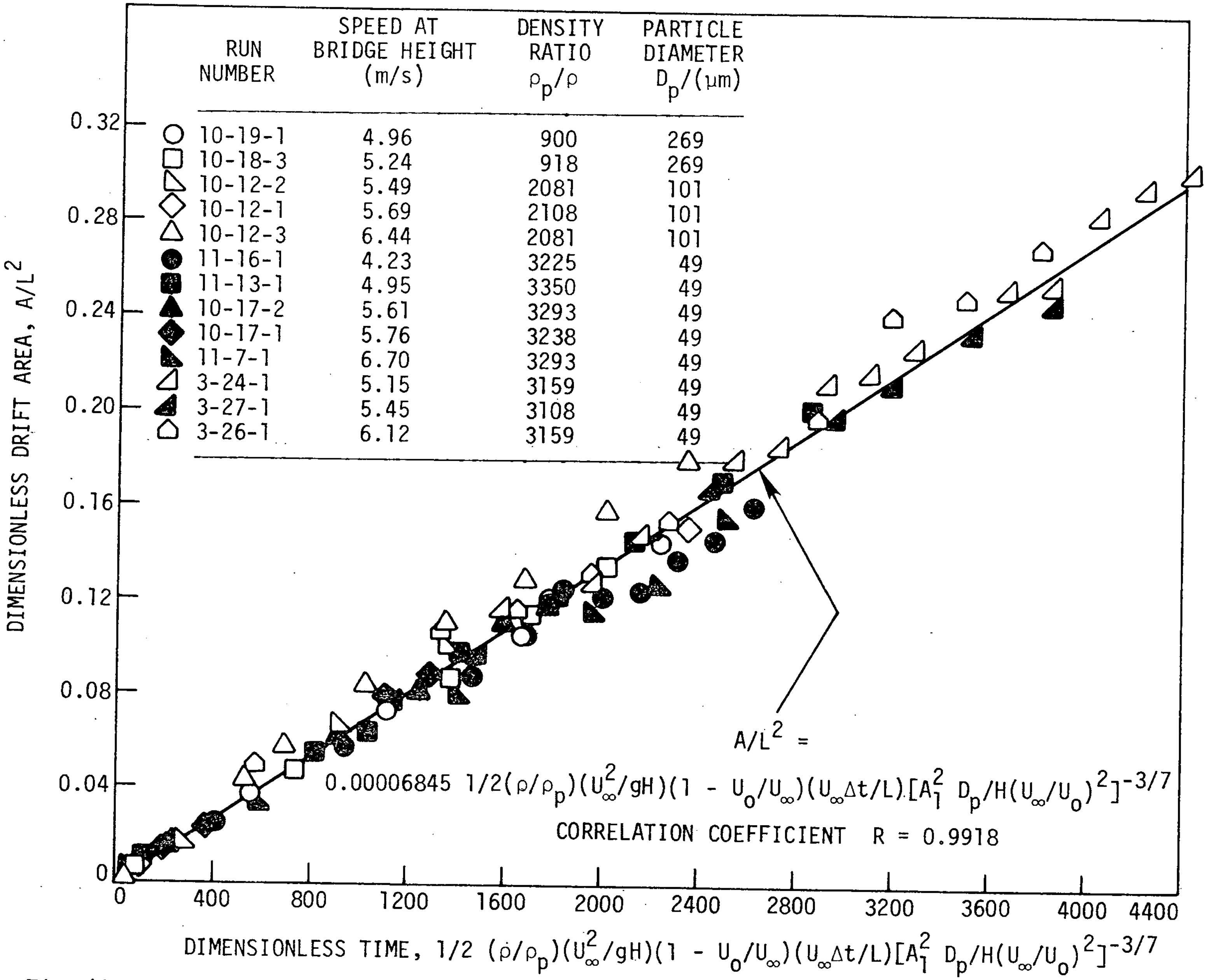


Fig. 41. Drift plan area accumulation of simulated snow as a function of the combined mass-rate roughness dimensionless time. Same data as Fig. 40.

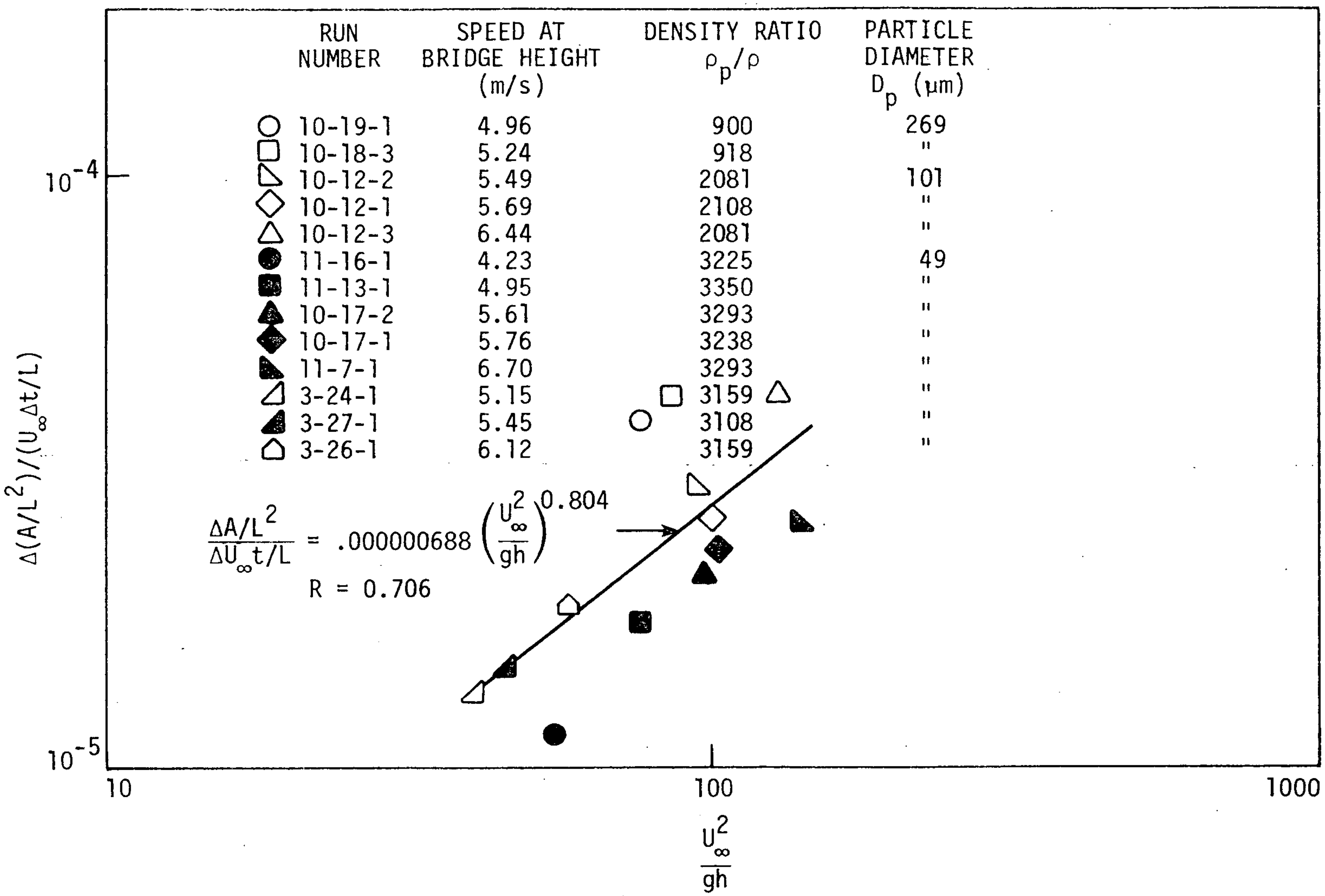


Fig. 42. Plan area drift rate at 0 deg wind direction (bare model) as a function of Froude number. Correlation coefficient R = 0.706.

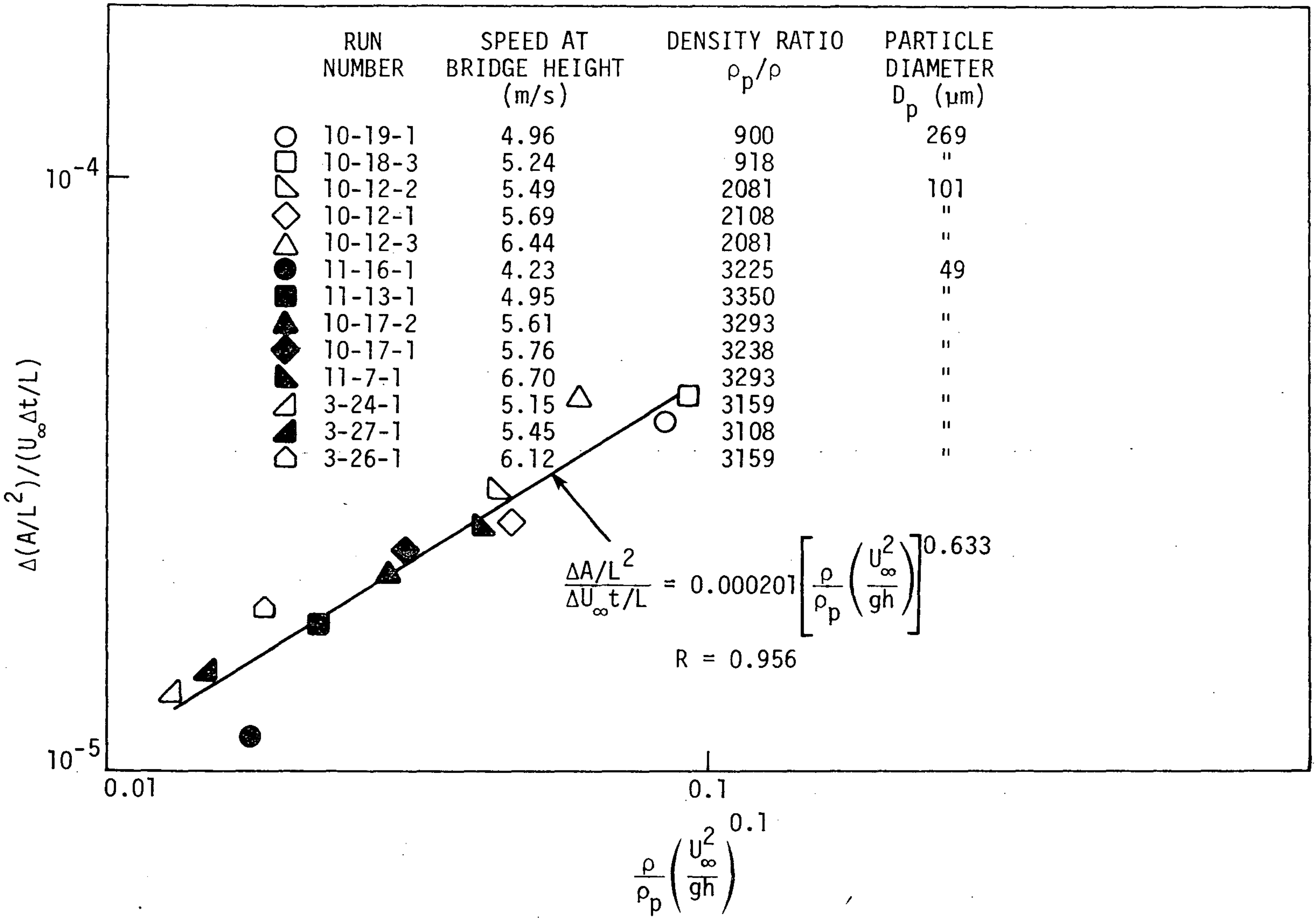


Fig. 43. Plan area drift rate at 0 deg wind direction (bare model) as a function of Froude number - density ratio product. Correlation coefficient R = 0.956.

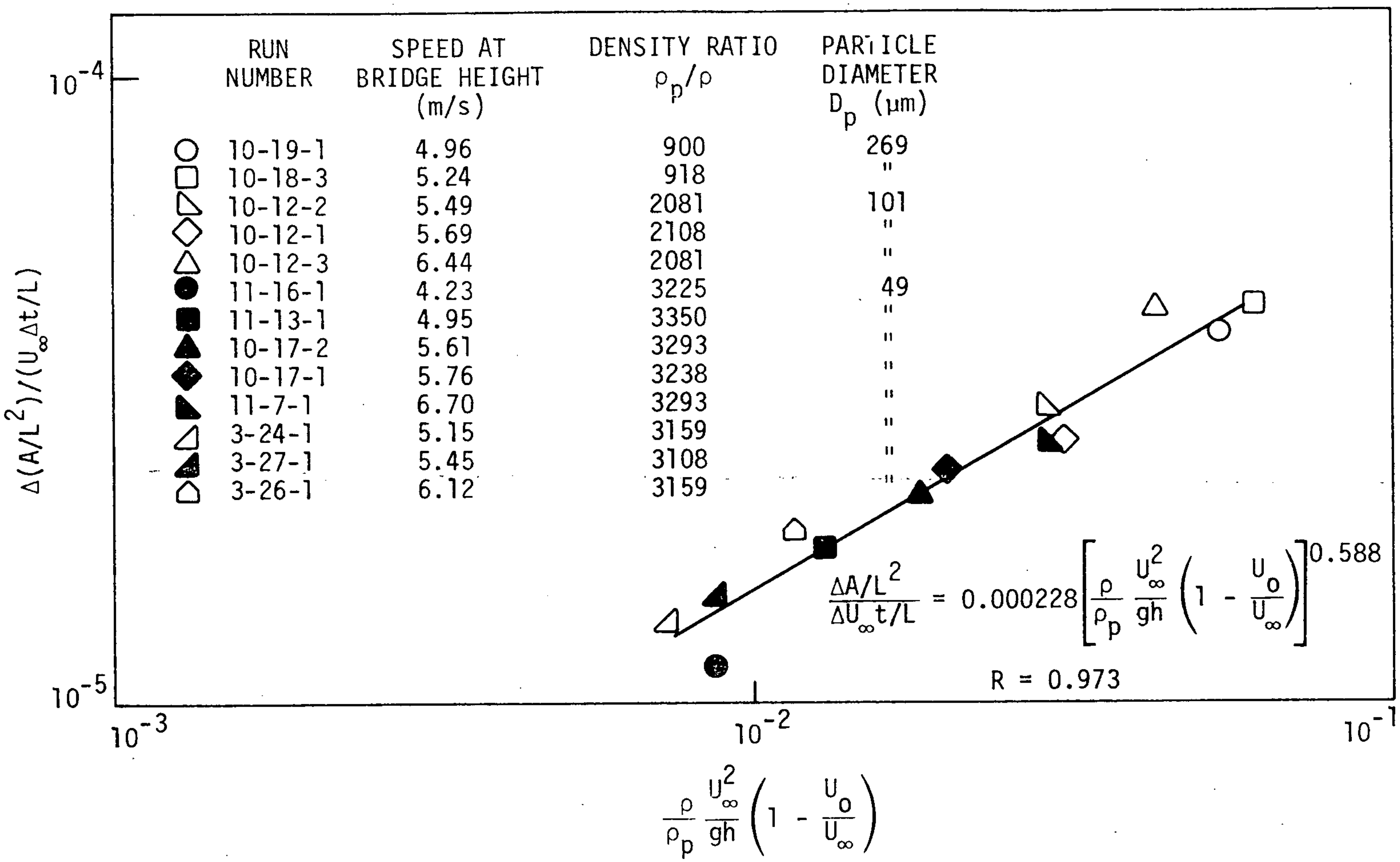


Fig. 44. Plan area drift rate at 0 deg wind direction (bare model) as a function of modified Froude number - density ratio product (mass-rate function). Correlation coefficient R = 0.973.

to R = 0.973, still not quite as good as the 0.983 in Fig. 39. Kind's expression (1976) for mass transport rate

$$q_s \sim \left[0.25 + \frac{1}{3}\frac{U_f}{u_{*_t}}\left(\frac{u_{*_t}}{u_*}\right)\right] \frac{\rho u_*^2}{g}\left(1 - \frac{u_{*_t}^2}{u_*^2}\right) \tag{44}$$

results in a correlation coefficient of R = 0.931 (0.967 if the bracketed coefficient, $[0.25 + U_F U_o/3u_{*_t} U_\infty]$, is neglected) and Kawamura's expression (1951)

$$q_s \sim \frac{\rho}{g}\left(u_* + u_{*_t}\right)^2 \left(u_* - u_{*_t}\right) \tag{45}$$

results in a correlation coefficient of R = 0.960.

The conclusions from the bare model calibration results are that:

1. The mass rate parameter is the most important parameter;
2. The current mass transport rate expression, Eq. (41), is the most accurate (R = 0.973, followed by Kind (modified), R = 0.967; Kawamura, 0.960; Bagnold, 0.956; and Kind, 0.931);
3. The equivalent roughness parameter is also important, R = 0.983, Fig. 39; and
4. The Froude number is not a correct scaling parameter for snowdrift simulation.

4.4. Testing of Simulated Vegetative Snowdrift Control

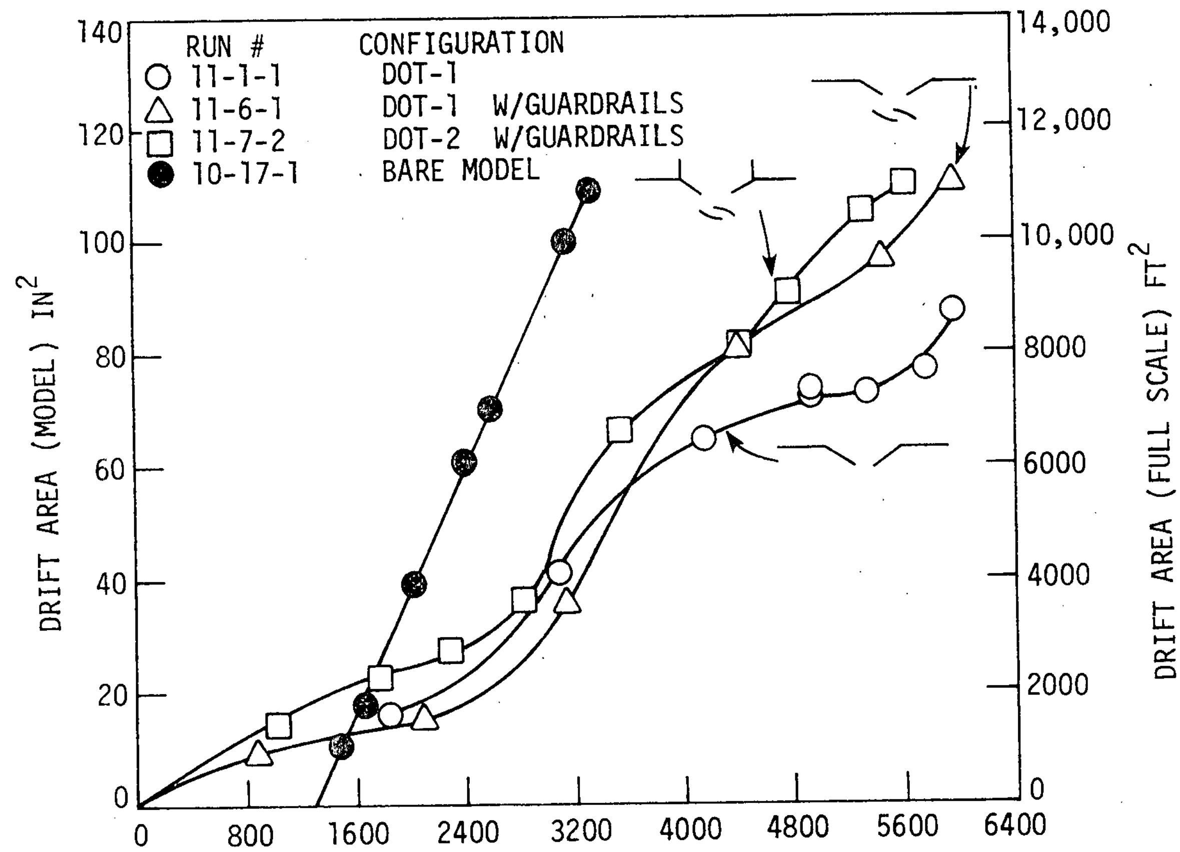
A total of 77 separate wind tunnel experiments were conducted with the two grade-separation models. Table 7 categorizes these experiments (Model 1 is the undistorted model; Model 2 is the vertically distorted model; see section 3.9).

Table 7. Categorization of grade-separation wind tunnel experiments.

Model	Wind Direction	Number of Experiments		Total Run Time	
		Bare Model	With Drift Control	Bare Model	With Drift Control
1	0^o	16	22	4:59 hr	9:41 hr
1	20^o	2	14	0:52 hr	4:41 hr
1	40^o	5	11	2:36 hr	5:58 hr
2	0^o	3	4	2:06 hr	4:01 hr
Totals:		26	51	10:33 hr	24:21 hr

Several, sometimes-conflicting philosophies were followed in designing plant-control configurations to be tested. Some configurations were placed wholly within typical right-of-way boundaries. Others were designed not using this constraint. Some configurations utilized solid barriers or deflectors as well as or instead of simulated vegetation. These results are not presented in the report body because implementation of solid barriers is probably impractical in the near future. Approximately 25 different control configurations were tested. The configuration geometry and basic test data for all 77 experiments are presented in the Supplement.

Results for the zero-degree wind direction are shown in Fig 45-52. One of the bare model calibration runs is shown in each figure for comparison with the drift control runs. Figure 45 illustrates the results for two existing Iowa Department of Transportation planting plans (DOT-1 and DOT-2). Two of the three drift control experiments were conducted with median guardrails in place. Late in the experiment the guardrails appear to have increased the drift area somewhat.



DIMENSIONLESS TIME $\frac{1}{2}\frac{\rho}{\rho_p}\frac{U_\infty^2}{gh}\left(1 - \frac{U_o}{U_\infty}\right)\frac{U_\infty \Delta t}{L}\left[A_1^2 \frac{D_p}{h}\left(\frac{U_\infty}{U_o}\right)^2\right]^{-3/7}$

Fig. 45. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-1-1, 11-6-1, and 11-7-2. Effect of plant configuration and median guardrail.

The proximity to the roadway of the portion of the plant configurations adjacent to the end of the bridge in the configurations of Fig. 45 cause increased initial drifting under the bridge on the upwind lane. Thus, before a dimensionless time value of about 1600, more snow is deposited on the upwind lane than without drift control. The conclusion from these four and other experiments is that the shoulder of the grade separation fill should not have any control plants on it and, in fact, should be kept as smooth as possible. Figure 46 illustrates a comparison with one of the more successful configurations. In this case (Run No. 11-22-1), the simulated snow drifting along the fill slope is trapped upwind of the shoulder and much less is deposited on the roadway at a given time.

Figures 47-50 illustrate several planting configurations with varying degrees of success. In Fig. 47 the two best configurations (lowest curve), in general, have control plant lines located farther upwind from the roadway. In Fig. 48 a minor improvement over the standard (DOT-1) plan is obtained by parallel rows of bushes located upwind on the fill slope (Run No. 11-10-5). In Fig. 49 three reversed versions (plant lines angle upwind rather than downwind) of the standard plan are shown. The results of Run No. 11-9-1 show what can happen when too many plants which are too tall are located too close to the roadway. Much more drifting occurs early in a storm than for the uncontrolled grade separation. In Fig. 50 and 51 the effect of a below-deck fairing on the road-facing lee-side fill slope (upwind end of bridge) is to obtain a very minor improvement in snowdrift control. It is believed, however, that an extensive (albeit probably impractical) streamlining of grade separation structures would

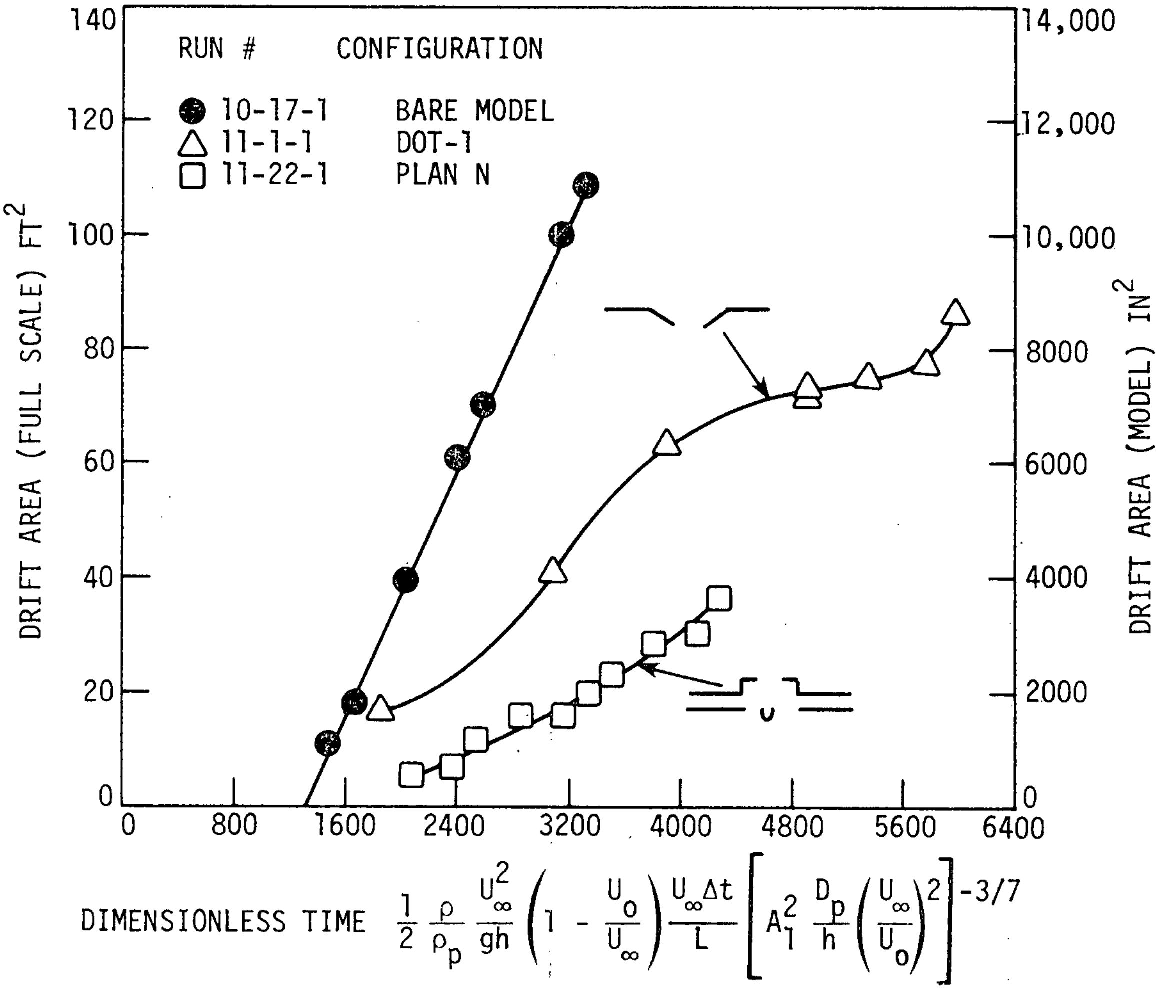


Fig. 46. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-1-1, 11-22-1. Effect of plant configuration.

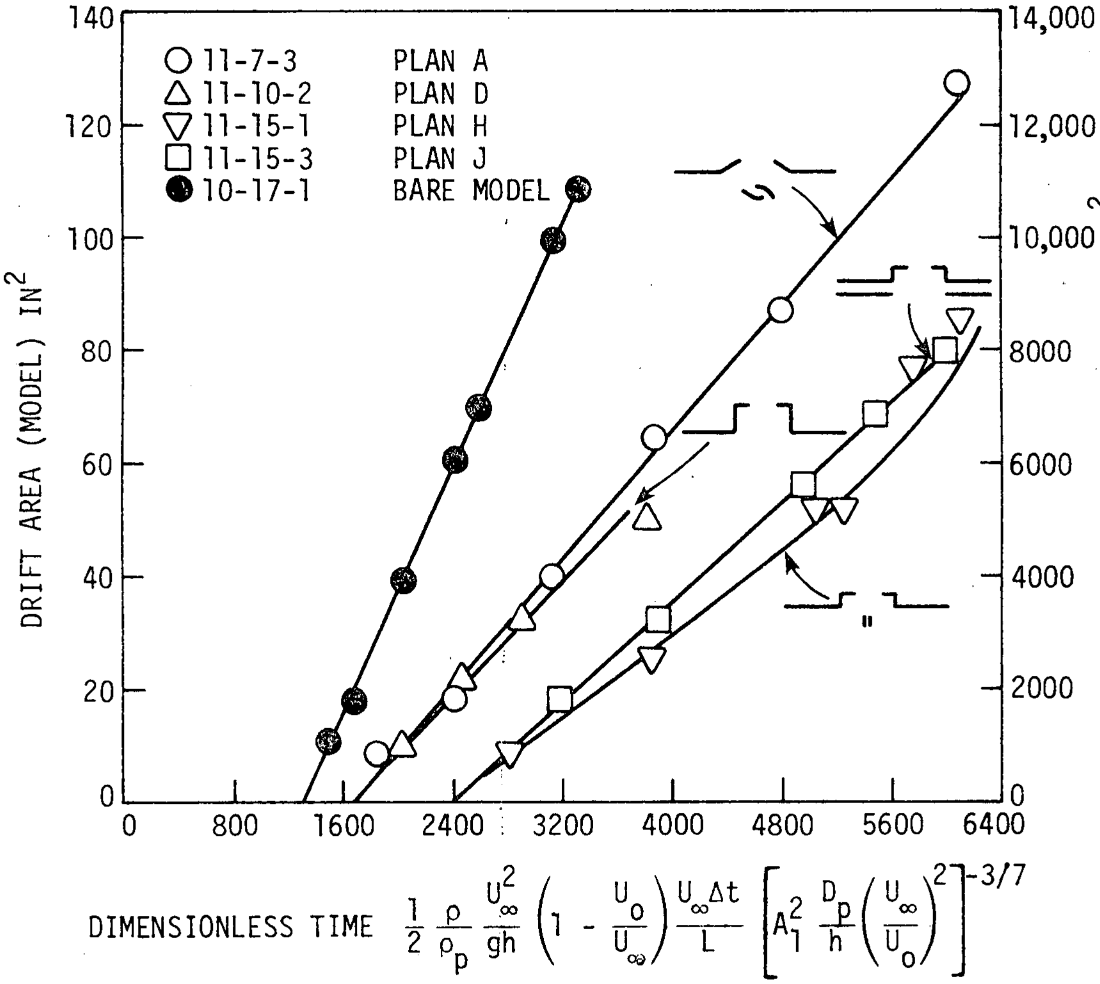


Fig. 47. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-7-3, 11-10-2, 11-15-1, 11-15-3. Effect of plant configuration.

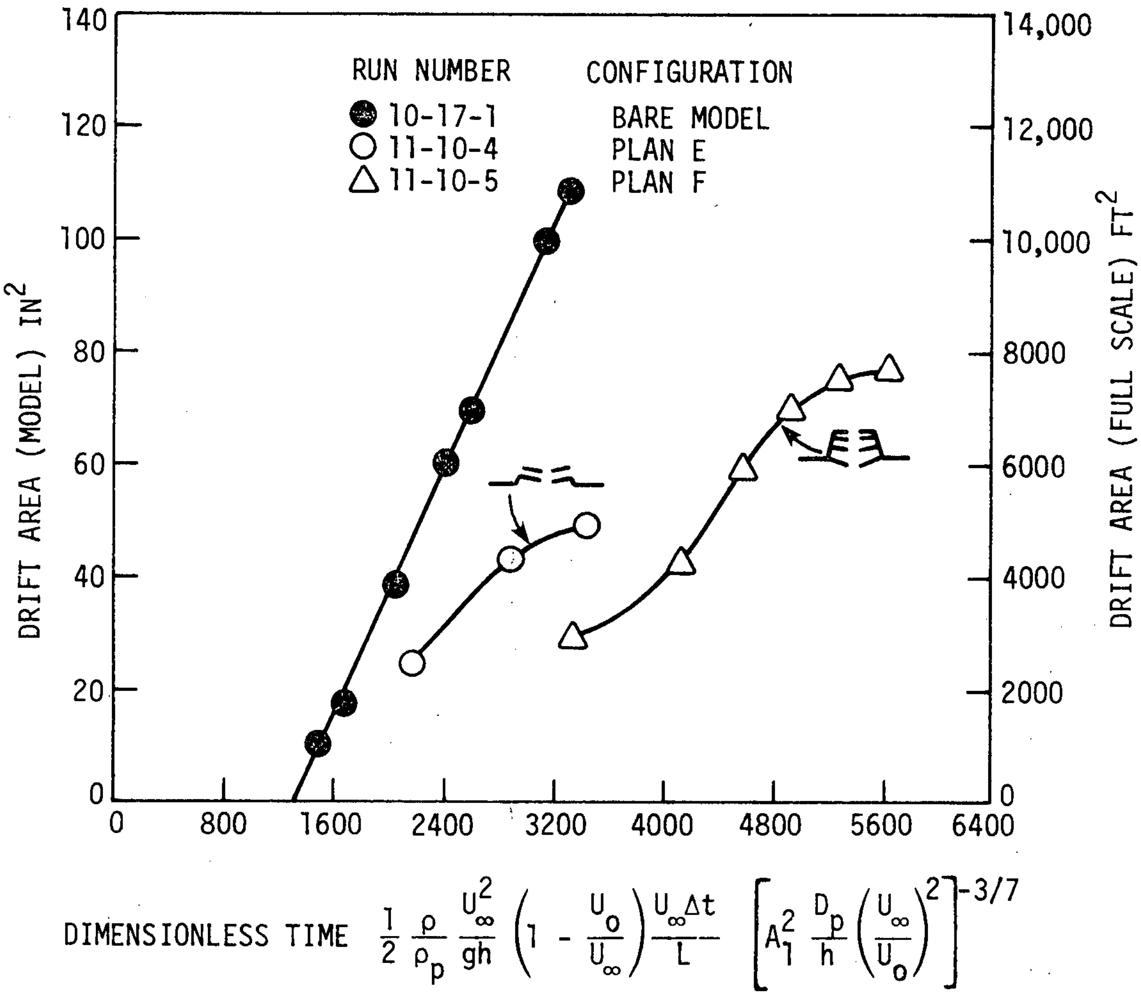


Fig. 48. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-10-4, and 11-10-5. Effect of plant configuration.

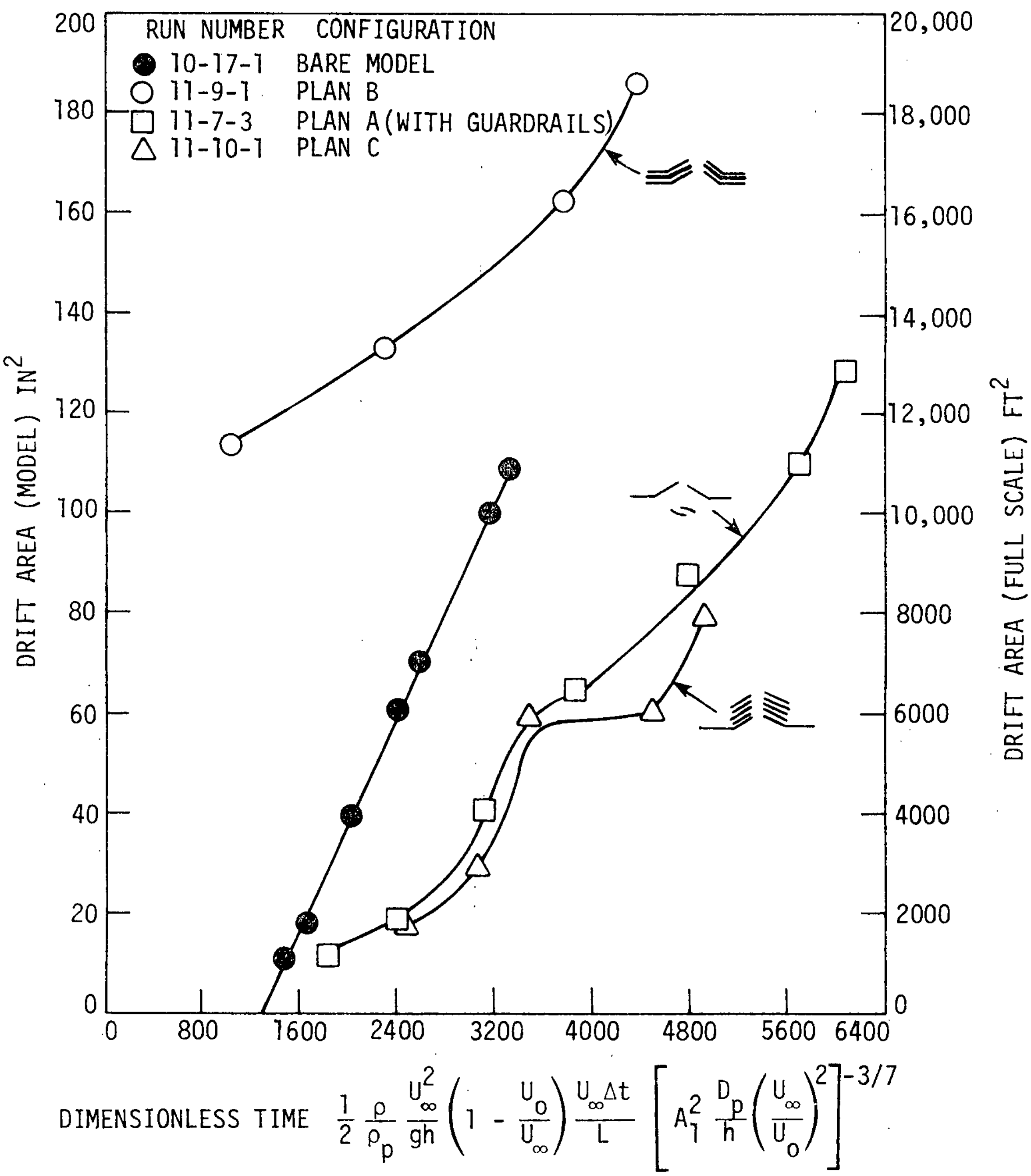


Fig. 49. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-7-3, 11-9-1, and 11-10-1. Effect of plant configuration.

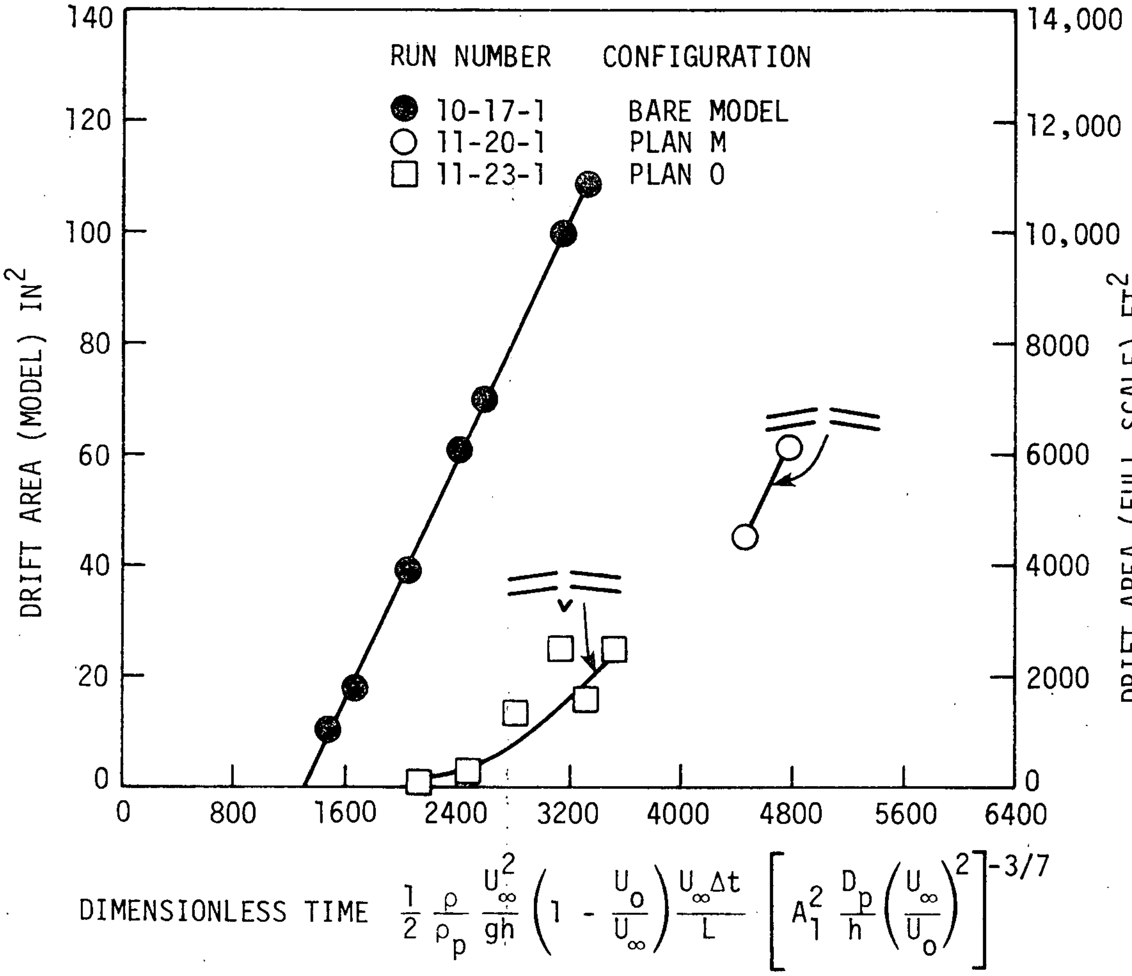


Fig. 50. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-20-1, and 11-23-1. Effect of bridge fairing.

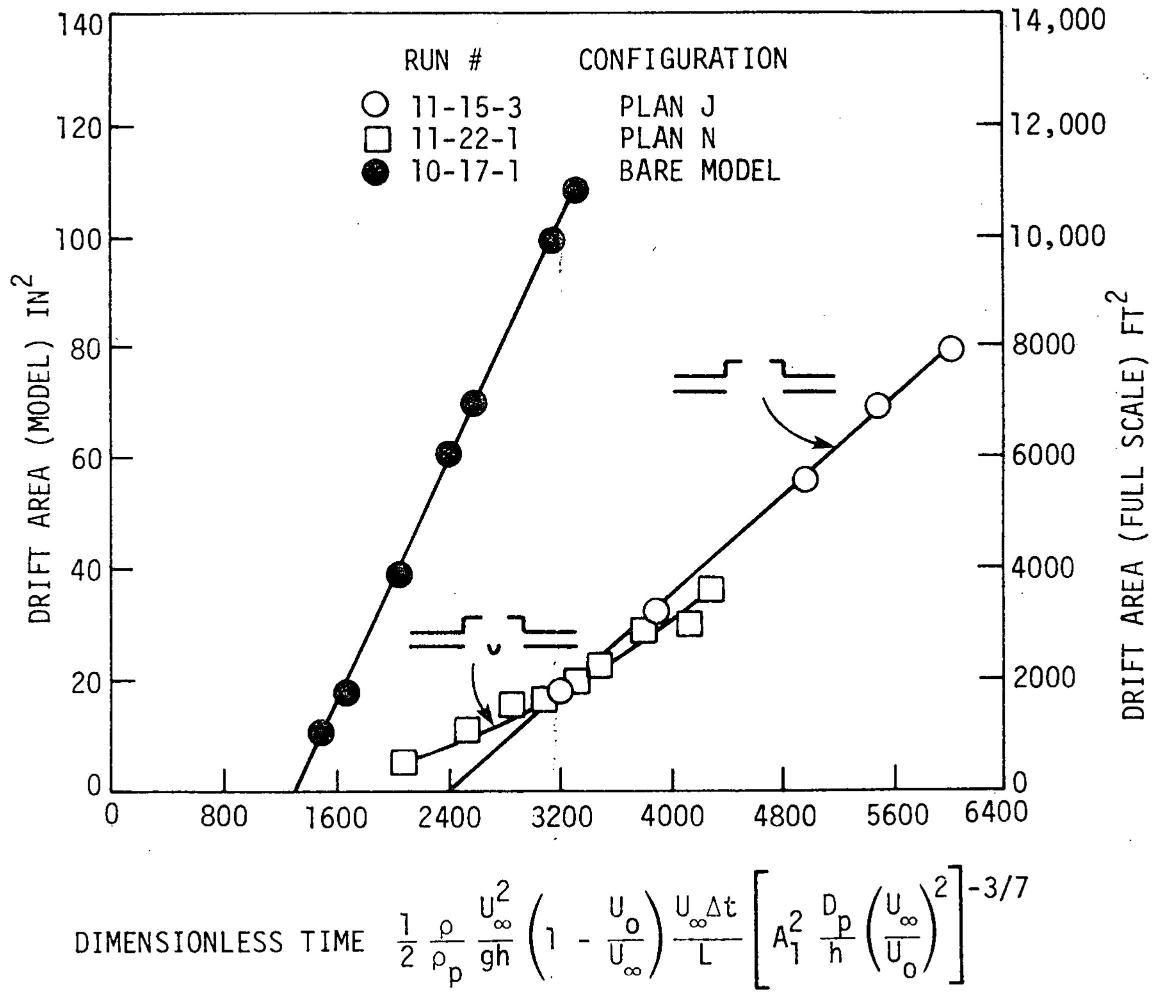


Fig. 51. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-15-3, and 11-22-1. Effect of bridge fairing.

aid in alleviation of the snowdrift control problem. Figure 52 shows that the median guardrails, while altering the road drift pattern somewhat, do not appreciably change the amount of drift accumulation at least for the uncontrolled model. Guardrails do present problems, however, in terms of snow removal and as a cause of drifting on bridges and bridge approaches.

The results of experiments with a free-stream wind direction at an angle of 20 deg to the bridge centerline are shown in Fig 53-58. A bare model test is illustrated in each figure for comparison purposes. The standard plan (DOT-1) again results in more drift accumulation than another of the better control configurations as shown in Fig. 53. Four of the configurations which were also tested at 0 deg wind direction were again tested at 20 deg. The results are shown in Fig. 54. The effect of bridge fairing length was surprisingly fairly large for one configuration, as shown in Fig. 55 while the difference between the short fairing and no fairing is small (Fig. 56).

The simulated bush material was shaped from packing material, similar to the material used in a standard furnace air filter. The normal "full bush width" was 1 in. wide and the height was also 1 in. (10 ft by 10 ft full scale). For Run No. 12-28-2 (Fig. 57), a bush width of 0.5 in. was used (creating an effectively more porous barrier) which was somewhat less successful. The reverse was true for the configurations in Fig. 58.

The results of the 40 deg wind direction experiments are illustrated in Fig 59-64. The results of the standard DOT-1 plan and plan D-40 are shown in Fig. 59. Again the DOT-1 plan results in greater drift area for both early and late times. The three rectangular plan configurations

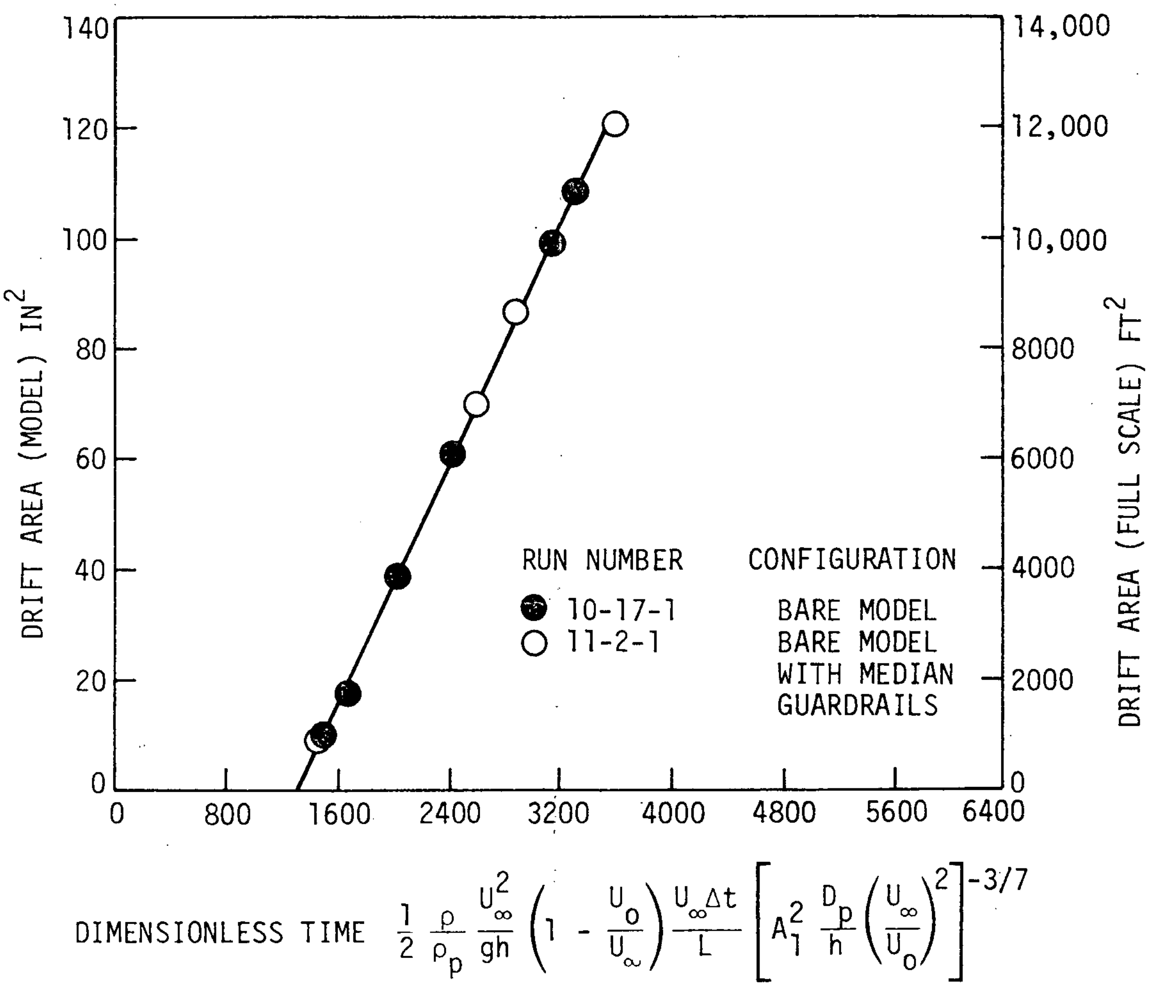


Fig. 52. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1 and 11-2-1. Effect of median guardrails.

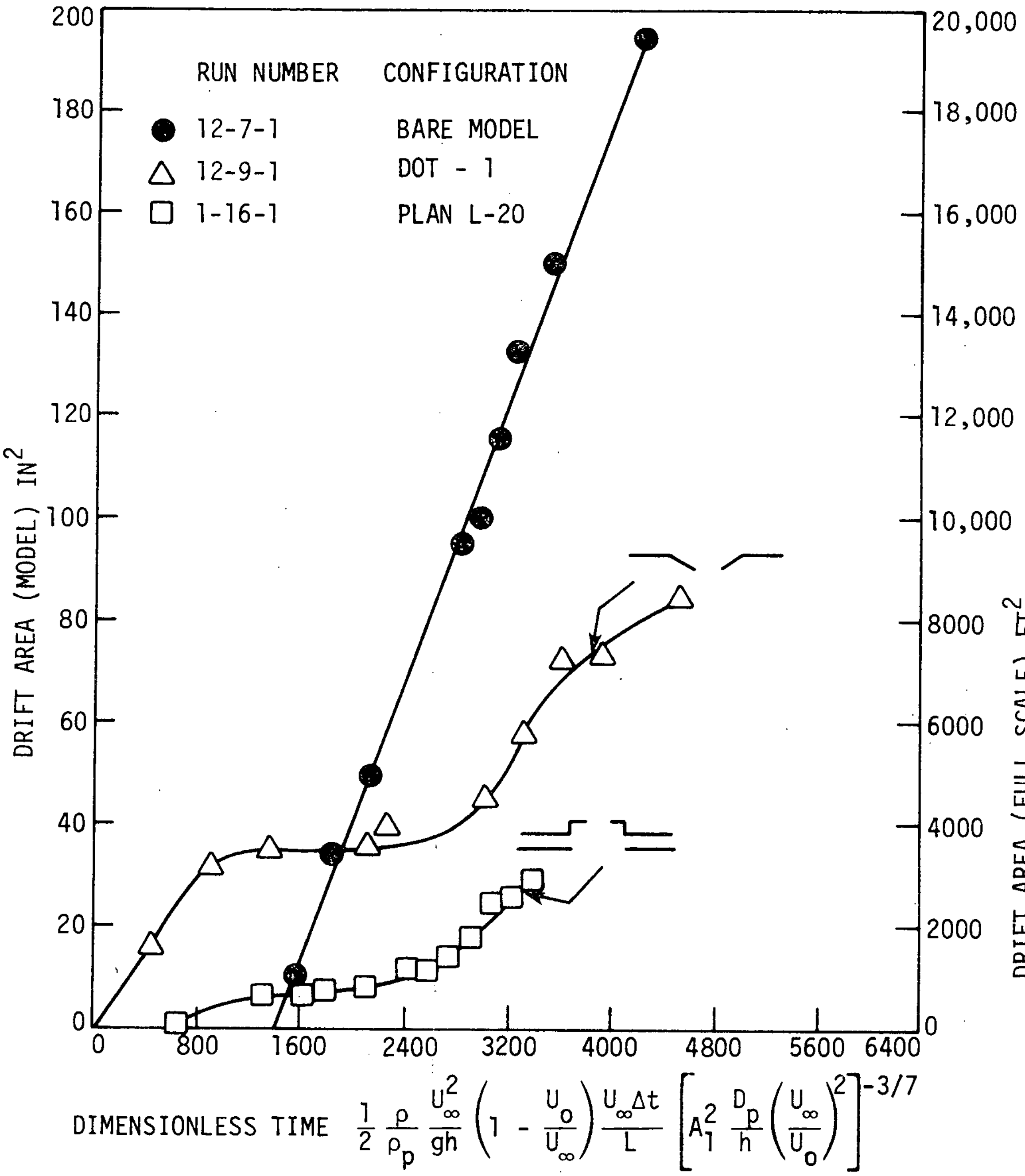
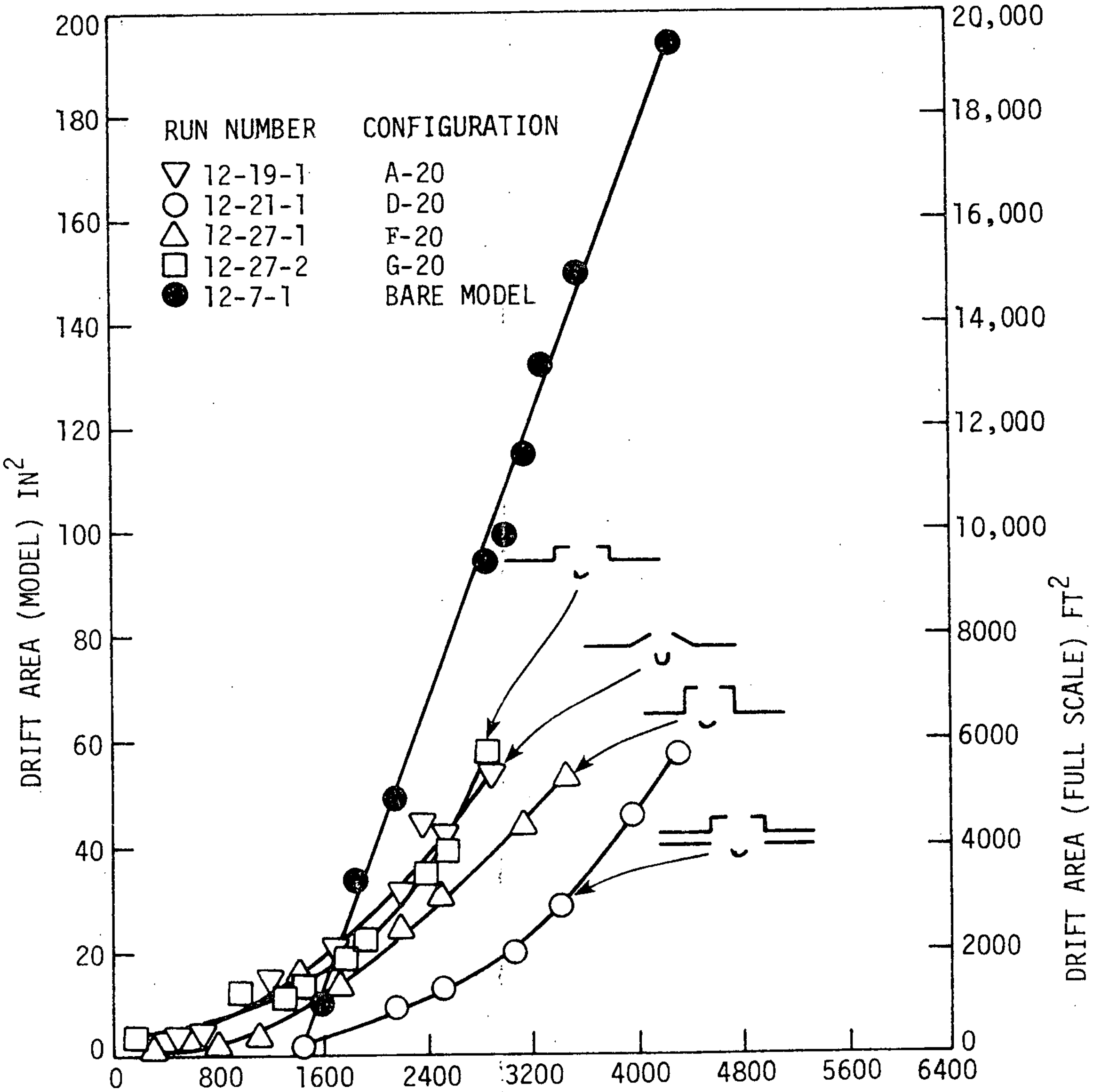


Fig. 53. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 20 deg to bridge centerline. Run No. 12-7-1, 12-9-1, and 1-16-1. Effect of plant configuration.



DIMENSIONLESS TIME $\frac{1}{2}\frac{\rho}{\rho_p}\frac{U_\infty^2}{gh}\left(1-\frac{U_o}{U_\infty}\right)\frac{U_\infty \Delta t}{L}\left[A_1^2\frac{D_p}{h}\left(\frac{U_\infty}{U_o}\right)^2\right]^{-3/7}$

Fig. 54. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 20 deg to bridge centerline. Run No. 12-7-1, 12-19-1, 12-21-1, 12-27-1, and 12-27-2. Effect of plant configuration.

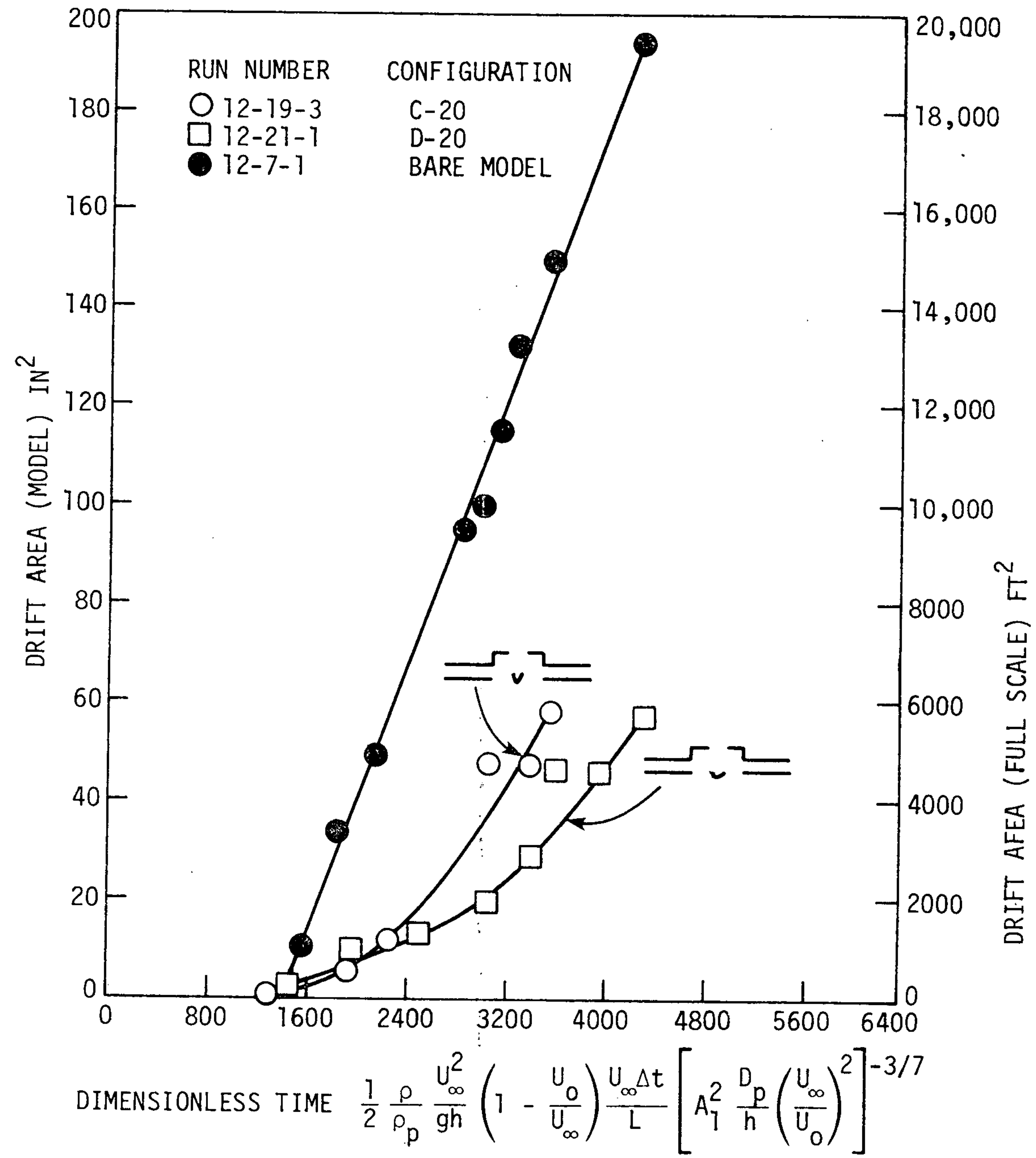


Fig. 55. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 20 deg to bridge centerline. Run No. 12-7-1, 12-19-3, and 12-21-1. Effect of bridge fairing length.

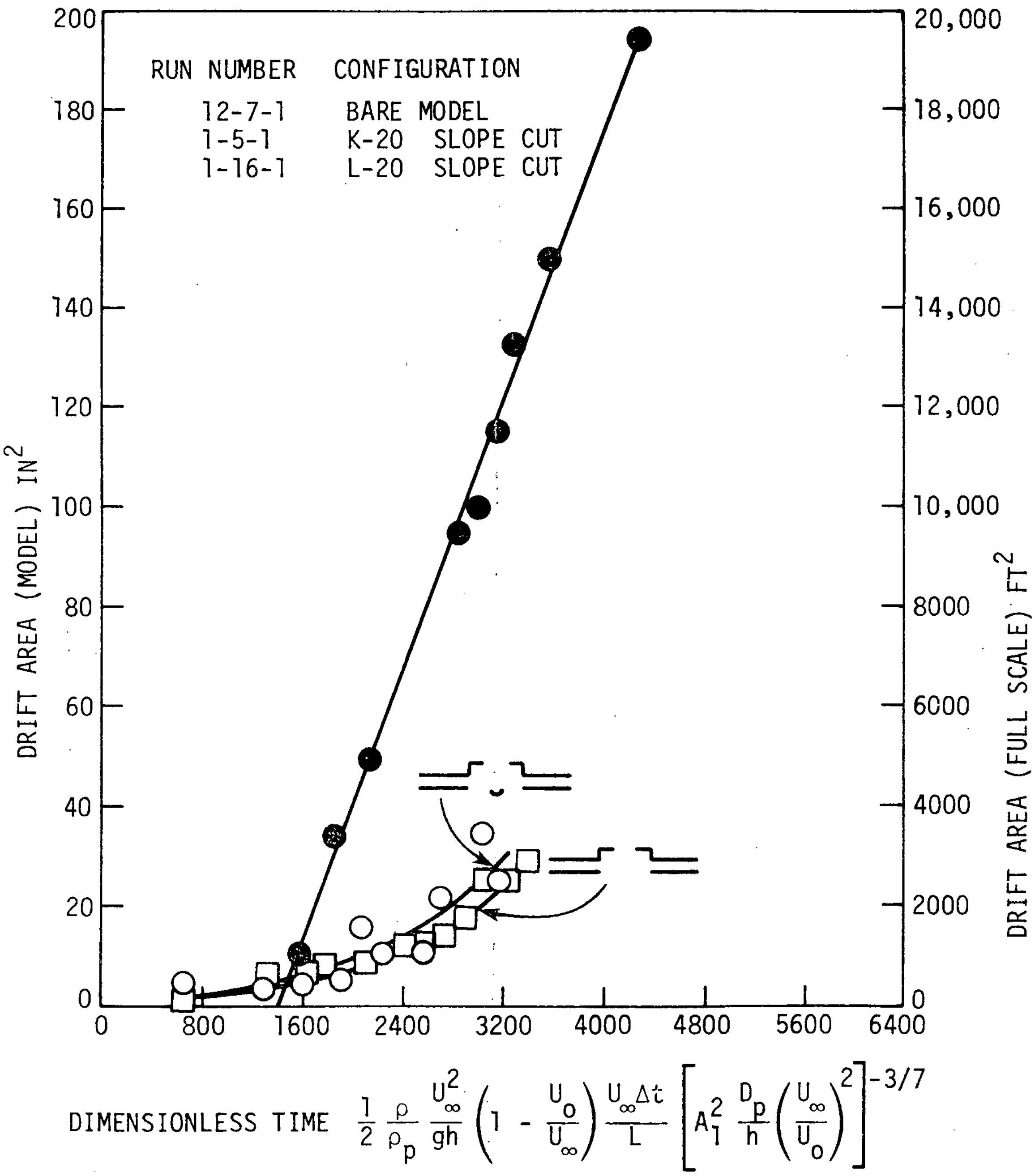


Fig. 56. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 20 deg to bridge centerline. Run No. 12-7-1, 1-5-1, and 1-16-1. Effect of bridge fairing.

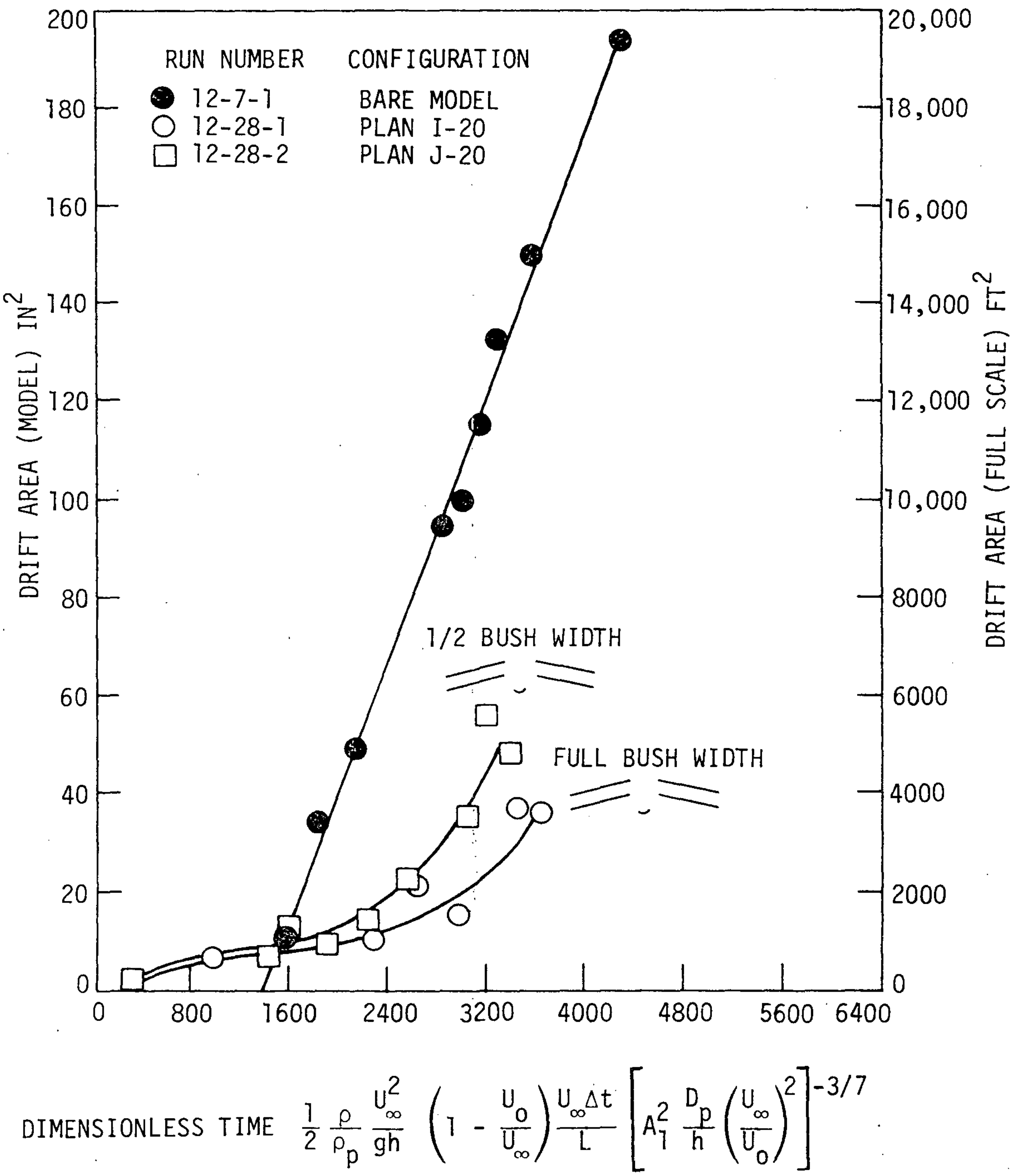


Fig. 57. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 20 deg to bridge centerline. Run No. 12-7-1, 12-28-1, and 12-28-2. Effect of simulated bush width.

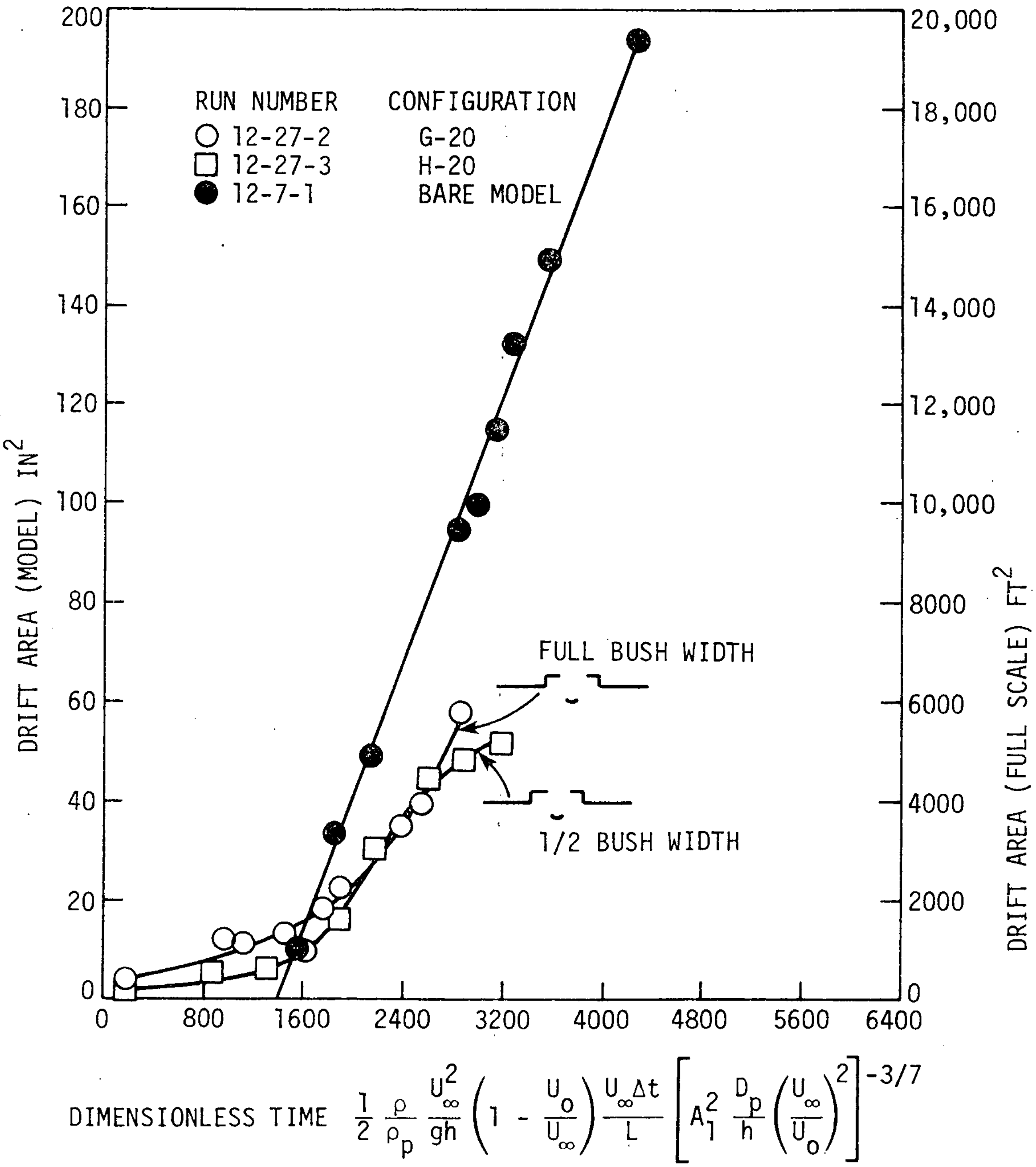


Fig. 58. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 20 deg to bridge centerline. Run No. 12-7-1, 12-27-2, and 12-27-3. Effect of simulated bush width.

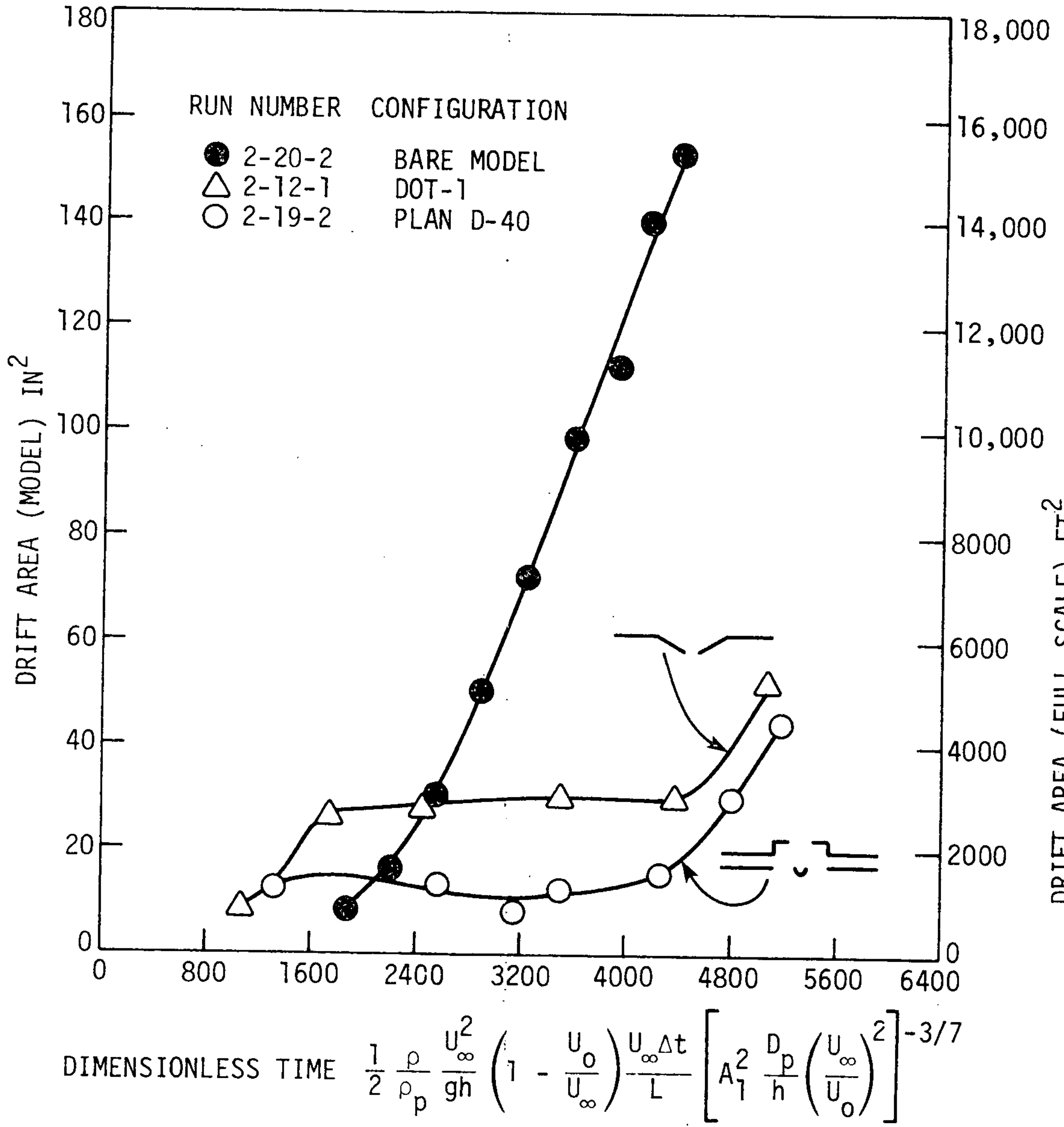


Fig. 59. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 40 deg to bridge centerline. Run No. 2-12-1, 2-19-2, and 2-20-2. Effect of plant configuration.

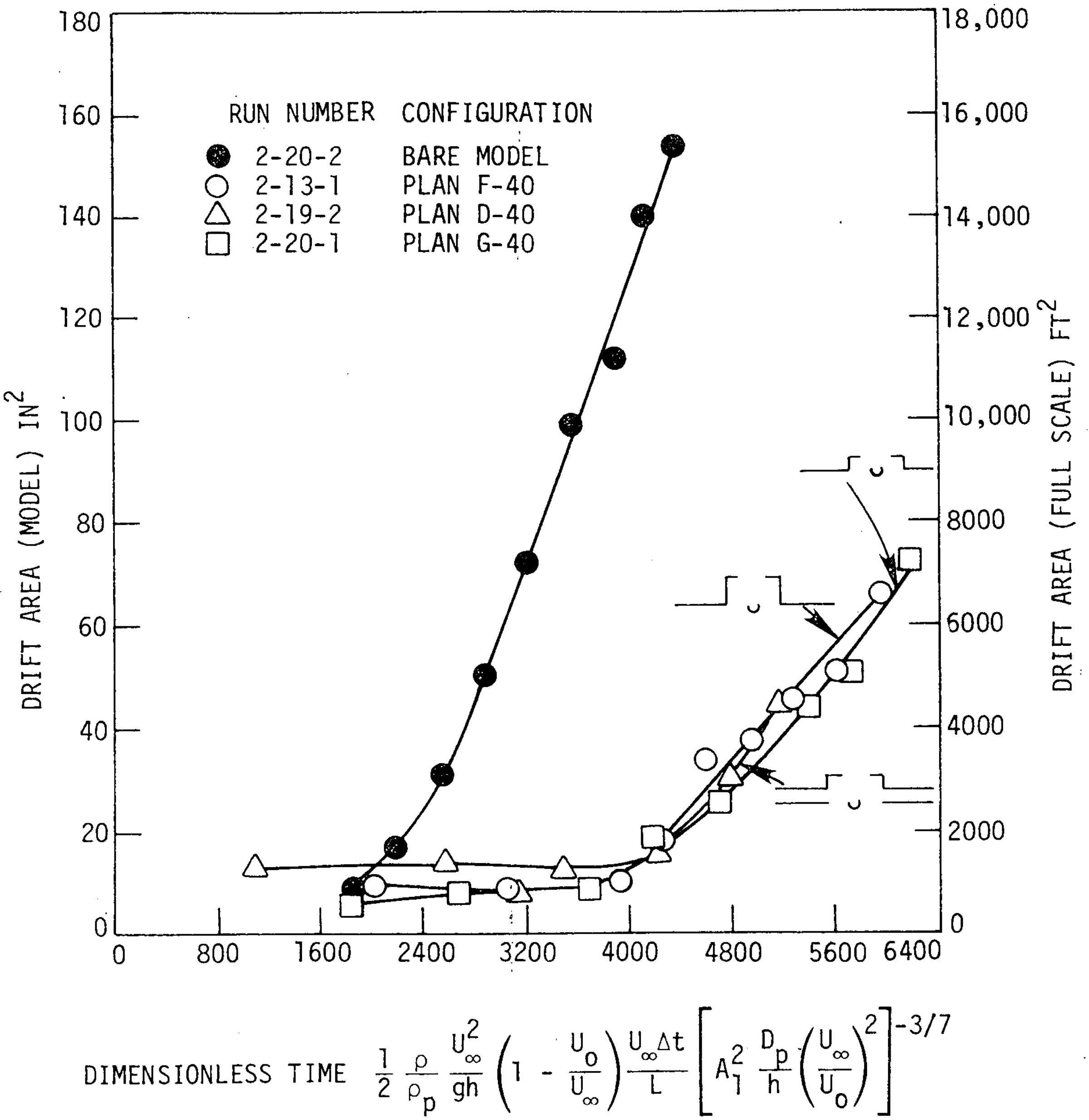


Fig. 60. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 40 deg to bridge centerline. Run No. 2-15-1, 2-19-1, and 2-20-2. Effect of plant configuration.

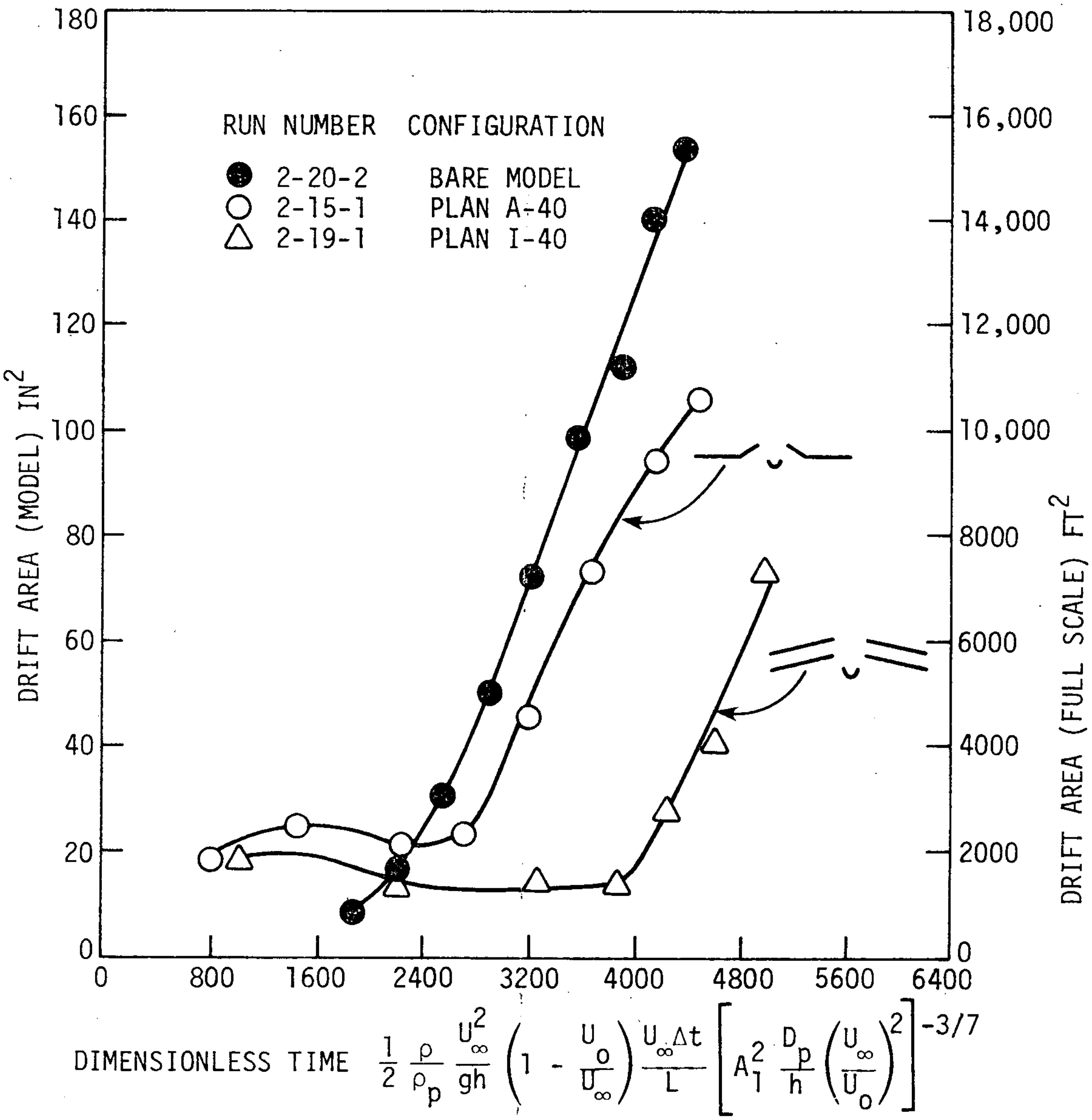


Fig. 61. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 40 deg to bridge centerline. Run No. 2-15-1, 2-19-1, and 2-20-2. Effect of plant configuration.

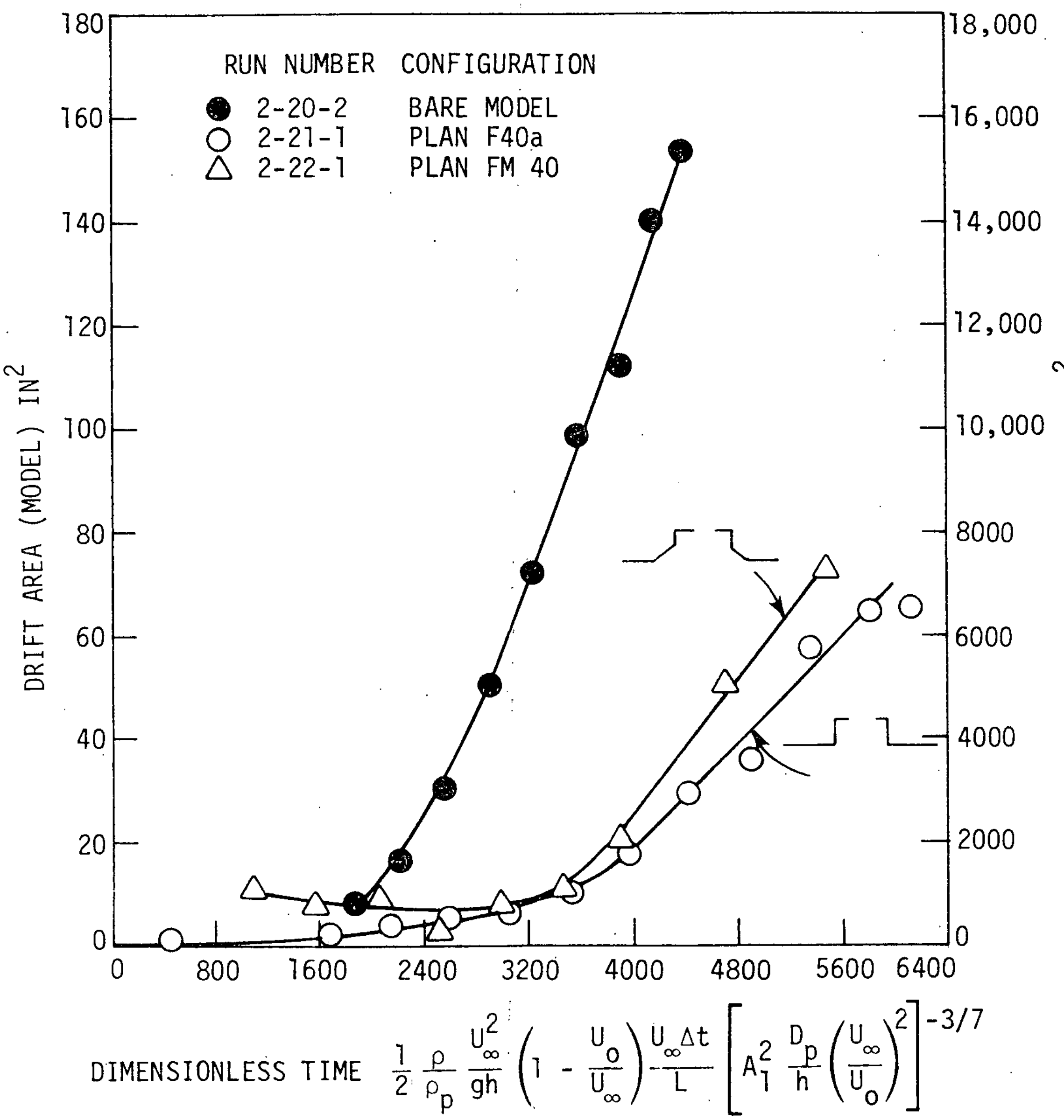


Fig. 62. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 40 deg to bridge centerline. Run No. 2-20-2, 2-21-1, and 2-22-1. Effect of plant configuration.

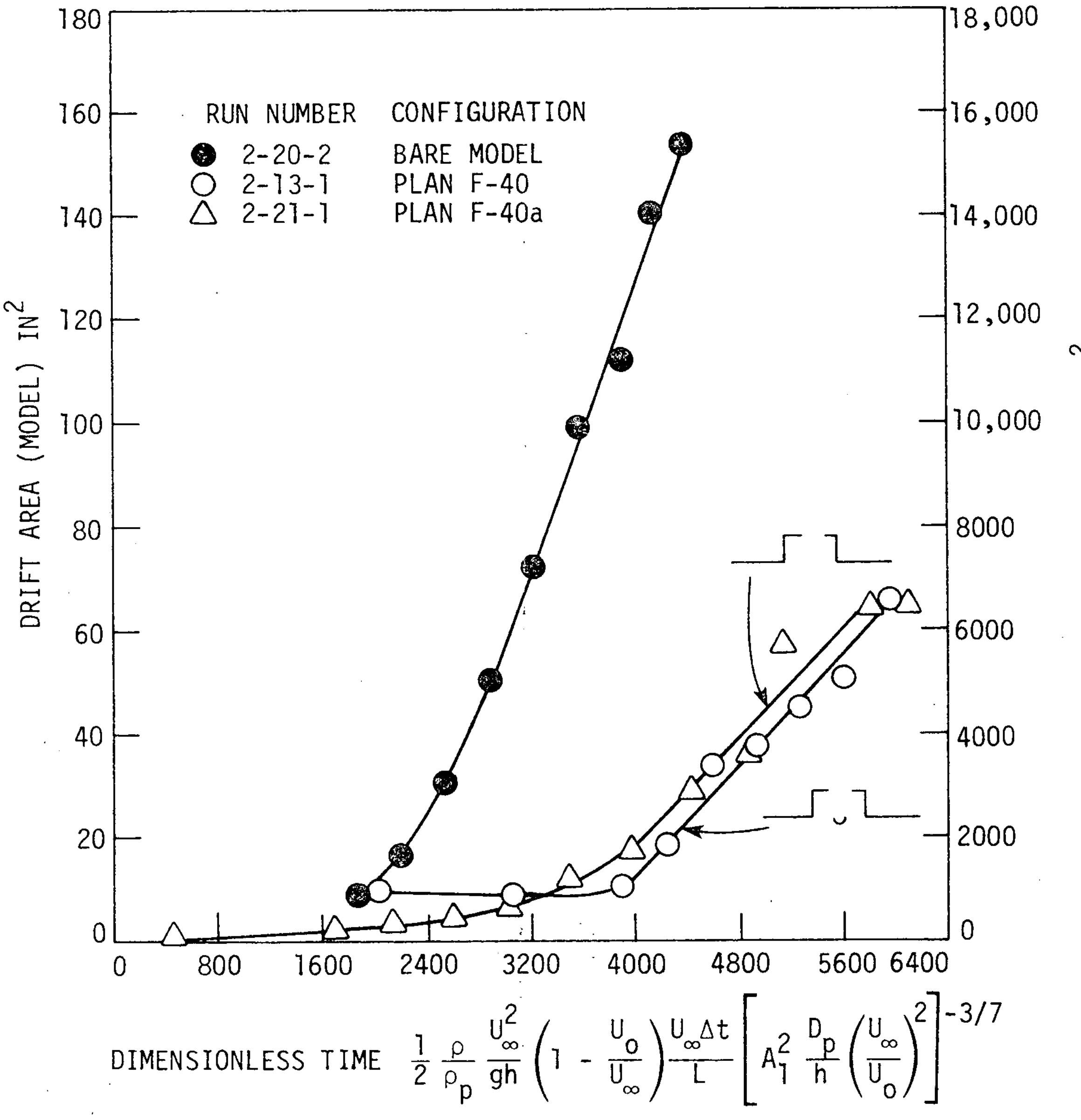
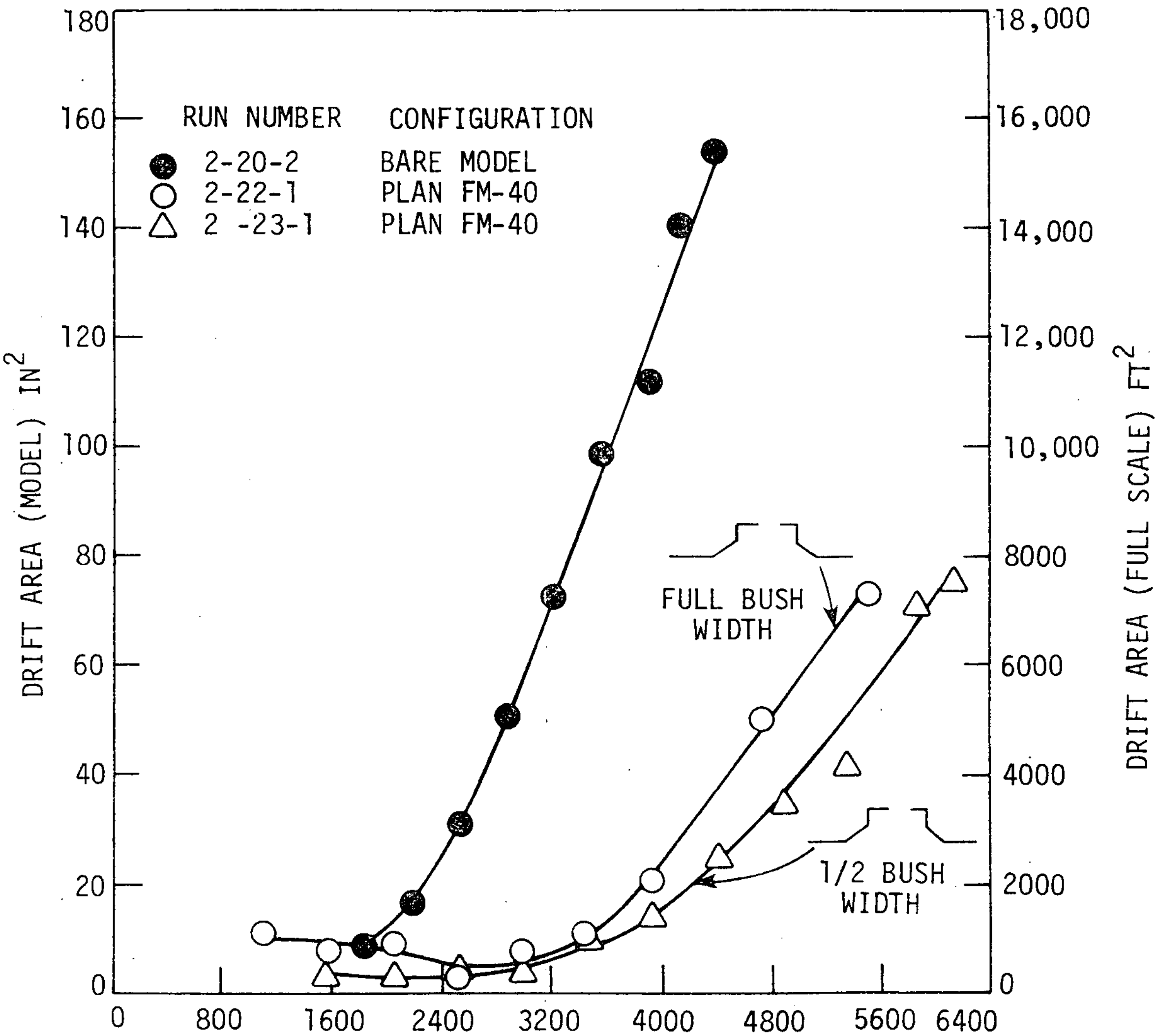


Fig. 63. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 40 deg to bridge centerline. Run No. 2-20-2, 2-13-1, and 2-21-1. Effect of bridge fairing.



DIMENSIONLESS TIME $\frac{1}{2}\frac{\rho}{\rho_p}\frac{U_\infty^2}{gh}\left(1 - \frac{U_o}{U_\infty}\right)\frac{U_\infty \Delta t}{L}\left[A_1^2\ \frac{D_p}{h}\left(\frac{U_\infty}{U_o}\right)^2\right]^{-3/7}$

Fig. 64. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 40 deg to bridge centerline. Run No. 2-20-2, 2-22-1, and 2-23-1. Effect of simulated bush width.

are very similar at 40 deg wind direction as seen in Fig. 60. Two other configurations which were also tested at 0 and 20 deg are illustrated in Fig. 61. A modification of plan F40 (plan FM40) was tried and found not to be quite as good as F40 (shown in Fig. 62). The effect of the bridge fairing was again shown to be small in Fig. 63. Finally, the effect of a more porous plant control (one-half bush width) in the case illustrated in Fig. 64 was to result in slightly improved drift control. Typical photographs of some of the experiments are illustrated in Fig. 65.

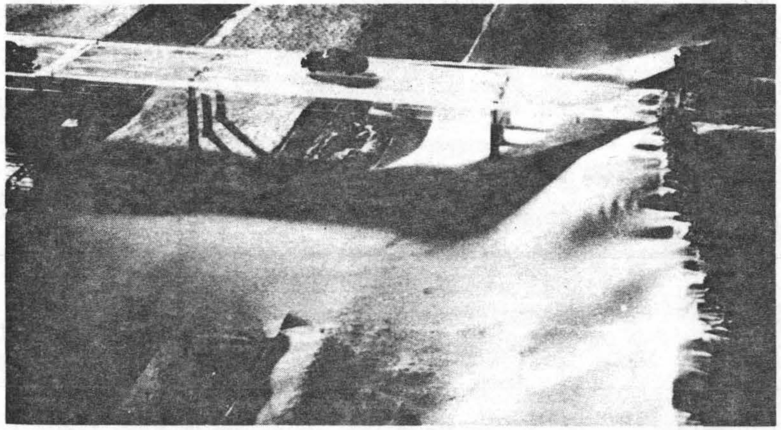
4.4.1. Figure of Merit

Three quantitative characteristics were chosen to establish a figure of merit for each model configuration. The three characteristics are:

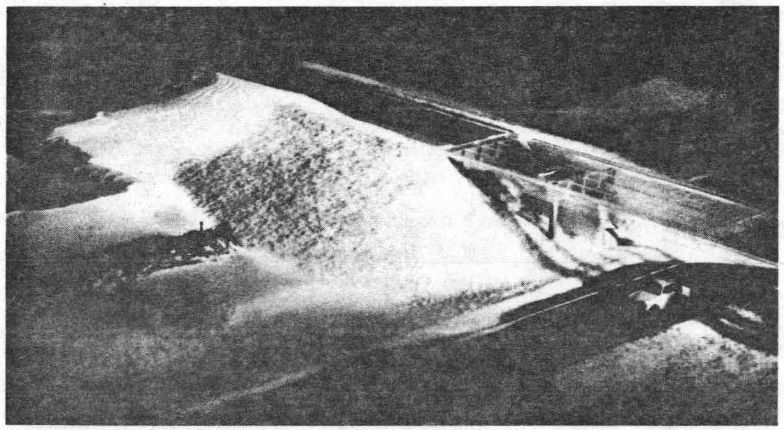
1. The dimensionless time at area A = 20 $in.^2$ divided by that value for the best configuration at that wind direction,
2. The dimensionless time at area A = 50 $in.^2$ divided by that value for the best configuration at that wind direction, and
3. The ratio of 100 $in.^2$ to the area A collected at the time when the bare model reaches 100 $in.^2$ divided by that ratio for the best configuration.

These numbers were added and averaged for each configuration. The results for the three wind directions are shown in Fig. 66.

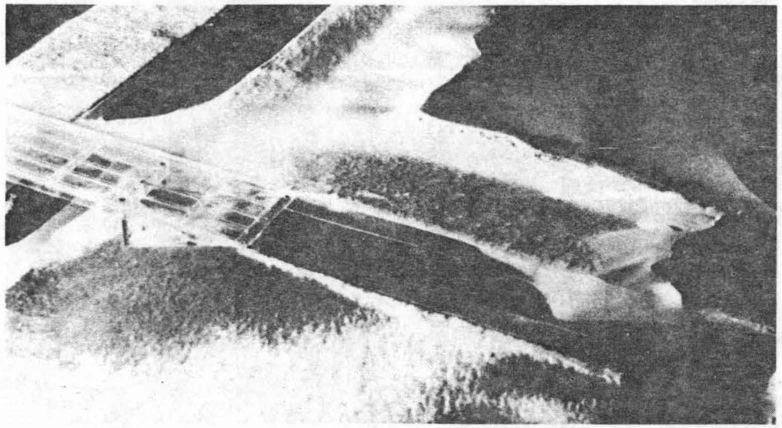
To obtain an overall figure of merit, the figures of merit for seven of the basic configurations including the bare model were averaged for all three wind directions. The results are shown in Fig. 67. A significant difference exists between the figures of merit for the top five configurations and the lower three (including the bare model). The reason for choosing 20 $in.^2$ and 50 $in.^2$ as the representative areas is that,



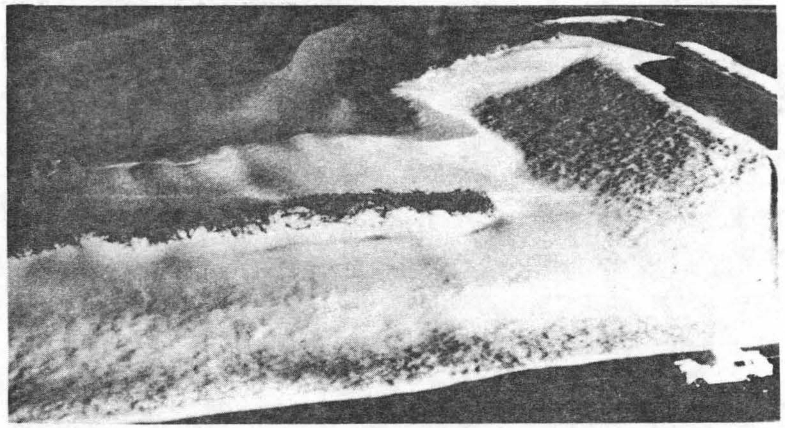
DOT-1 plan (run 12-9-1). Wind direction 20° right to left.



Plan C-20 (run 12-19-3). Wind direction 20° left to right.



Plan F-40 (run 2-13-1) within typical right-of-way boundaries. Wind direction 40° right to left.



Plan D-40 (run 2-14-1). Wind direction 40° left to right.

Fig. 65. Photographs of simulated plant drift-control configurations. Wind tunnel tests at 20 and 40 deg wind directions for Model 1.

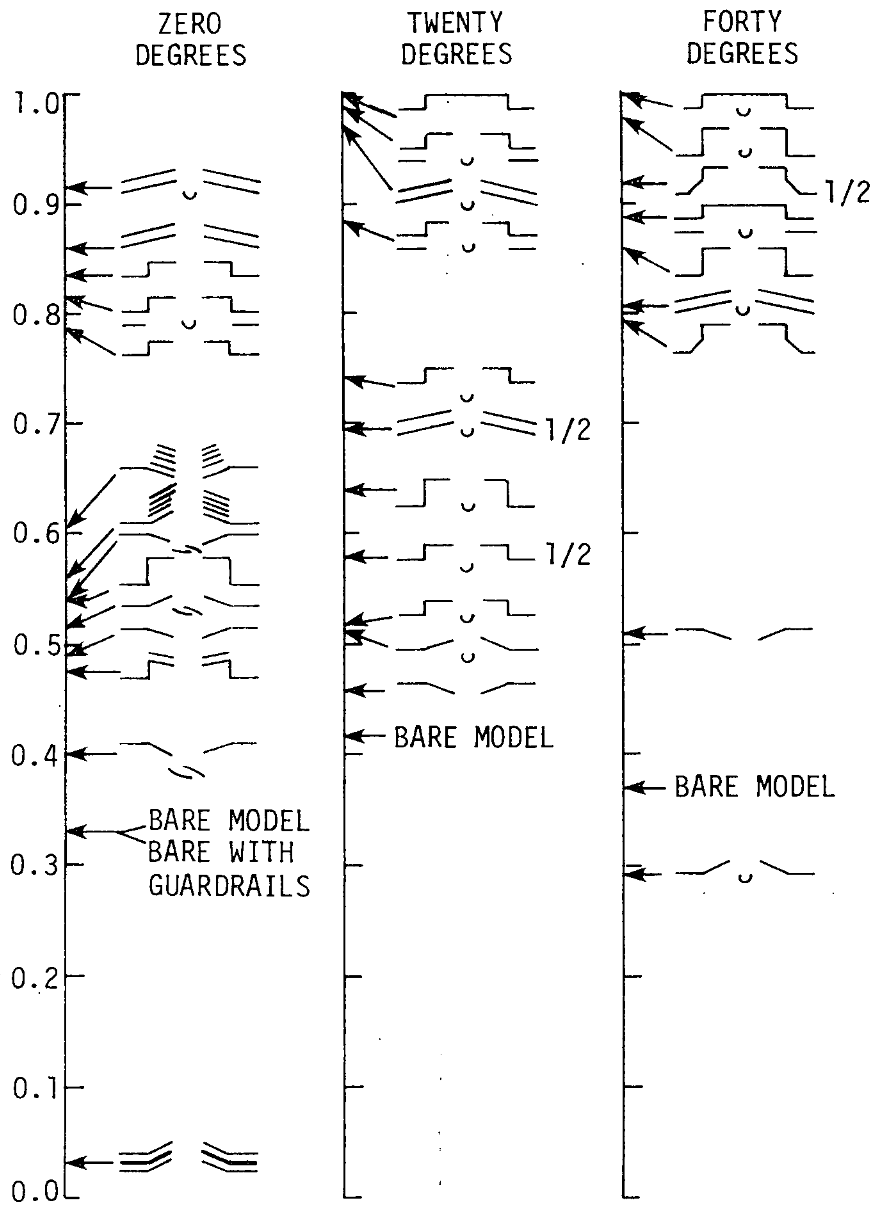


Fig. 66. Figures of merit (vertical scale at left) for various snow-drift control configurations for the three wind directions. Those configurations with higher figures of merit have more effective drift control capability.

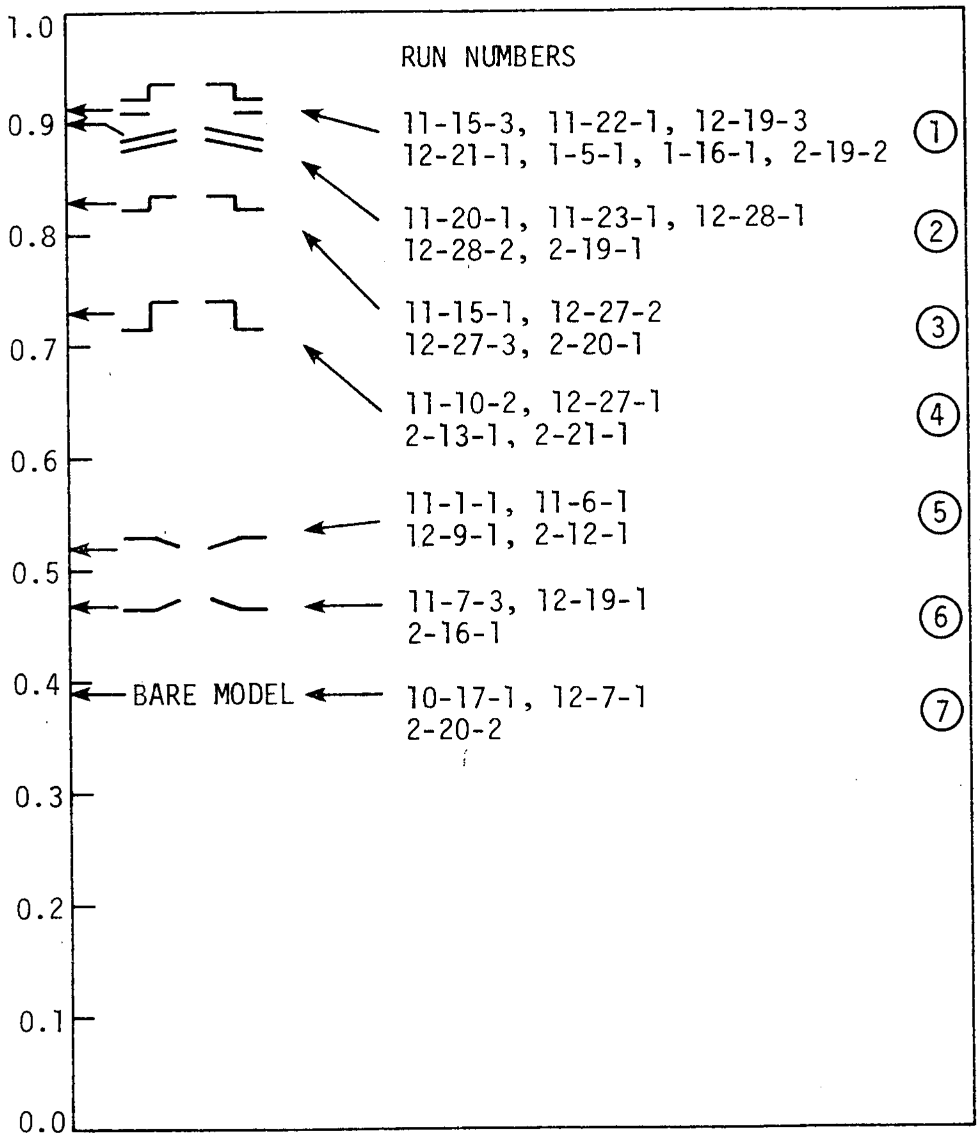


Fig. 67. Figures of merit (vertical scale at left) for various snow-drift control configurations calculated by averaging values for the three wind directions. Those configurations with higher figures of merit have more effective drift control capability.

with some configurations, a nearly immediate drifting results which is greater than 20 but less than 50 in.^{2} in area. Thus, the 20 in.^{2} figure refers to drifted snow resulting from low energy separated flow from the fill and from the plant arrangements or other obstacles. By the time 50 in.^{2} has drifted over, however, the primary drifting mode is usually from saltation outside of the separated flow regions. Configurations 1, 2 and 3 in Fig. 67 contain plant control lines outside of the typical right-of-way boundaries. Configurations 4, 5 and 6 contain plant control lines inside the typical right-of-way boundaries. Thus, the best control is obtainable only where there is sufficient room, such as at a complete interchange or if additional right-of-way is purchased.

4.4.2. Results for the vertically distorted Model 2

The results with the vertically distorted model at 0 deg wind direction for one bare model experiment and one controlled model experiment are shown in Fig. 68, along with the corresponding results for the undistorted Model 1. The results for both configurations are displaced to the left for Model 2 compared with Model 1. The reason for this is that Model 2 is effectively distorted horizontally as well as vertically where there are separated flow or reduced speed regions such as the lee side of the fill slope under the bridge and downwind of the simulated plant control. Because of the greater relative height of the fill slope and plant control in the distorted Model 2, the regions of reduced speed extend farther downwind than in the undistorted Model 1 (or in full scale). Thus, early drifting occurs farther downwind for Model 2 than for Model 1 and the drift area on the roadway is larger for corresponding times as shown in Fig. 68. That Model 2 still gives valid relative results at

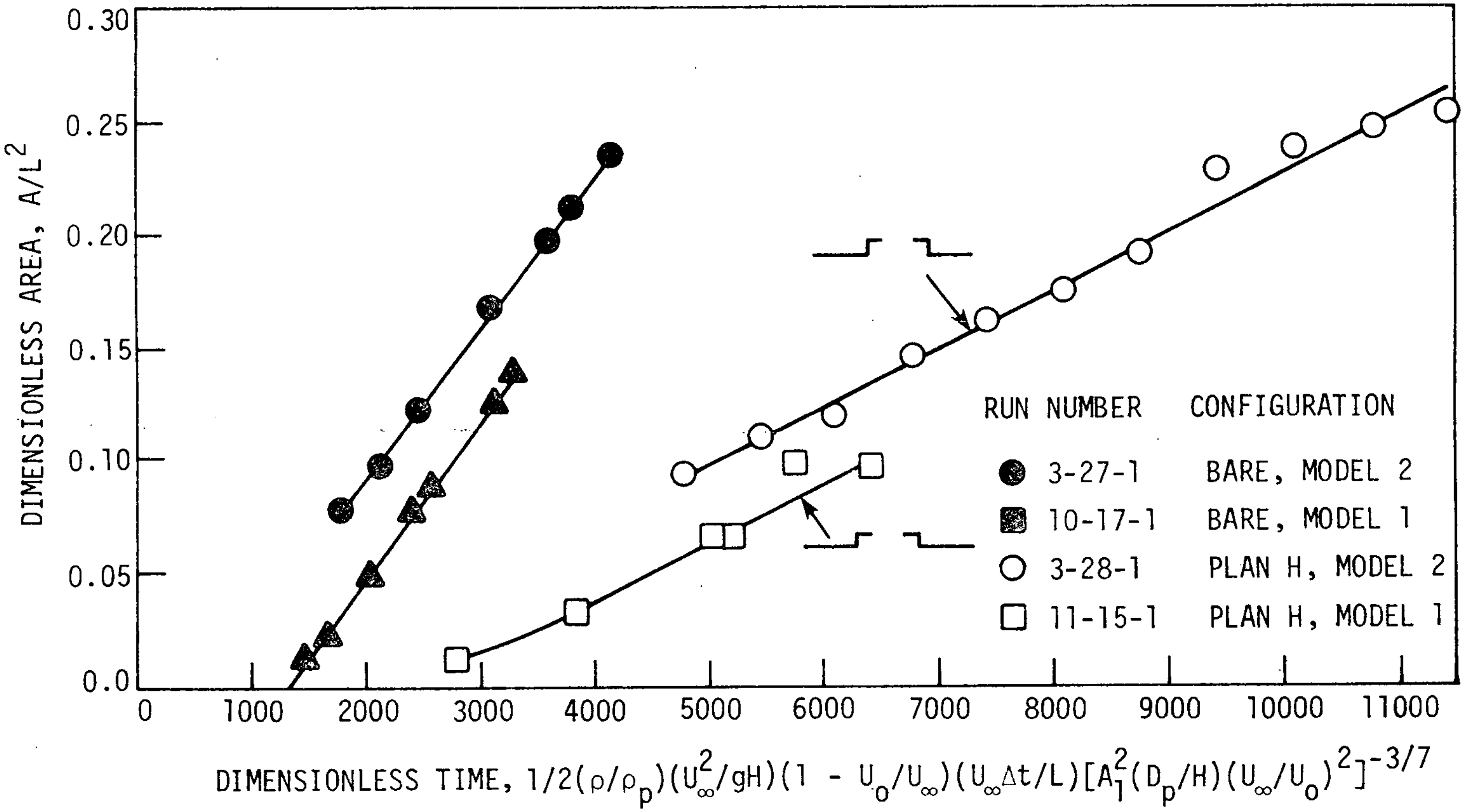


Fig. 68. Drift plan area accumulation of simulated snow as a function of dimensionless time. Wind direction at an angle of 0 deg to bridge centerline. Run No. 10-17-1, 11-15-1, 3-27-1, and 3-28-1. Effect of vertical distortion of Model 2.

least for certain configurations is shown by the fact that the two sets of curves are parallel and displaced vertically about the same distance.

4.5. Extrapolation of Model Results to Full Scale

Previous investigators have usually used the Froude number U^2/gL as a means of determining the full scale wind speed and modeled snow storm time duration. This is believed to be incorrect according to the preceding similitude analysis and wind tunnel test results. If, however, the Froude number is used as a means of extrapolation, then the full scale to model wind speed ratio U/U_m would just be the square root of the length ratio L/L_m. The time ratio $\Delta t/\Delta t_m$ would be the same value as the speed ratio. Using Run No. 10-17-1 as an example (model speed = 5.76 m/sec and time duration = 18 min), the full-scale wind speed would be 63.05 m/sec (141 mph) and the duration would be 3 hr and 17 min, which are not very realistic values.

According to the wind tunnel results of the 13 bare model experiments, the appropriate extrapolation is to equate the mass-transport rate roughness parameters for model and full scale:

$$(\Delta A/L^2)\left[A_1^2\,\frac{D_p}{h}\left(\frac{U}{U_o}\right)^2\right]^{3/7}\Bigg/\left\{\frac{\rho}{\rho_p}\,\frac{U^2}{gh}\left(1-\frac{U_o}{U}\right)\frac{U\Delta t}{L}\right\}\Bigg|_{\text{Model}}$$
$$= (\Delta A/L^2)\left[A_1^2\,\frac{D_p}{h}\left(\frac{U}{U_o}\right)^2\right]^{3/7}\Bigg/\left\{\frac{\rho}{\rho_p}\,\frac{U^2}{gh}\left(1-\frac{U_o}{U}\right)\frac{U\ t}{L}\right\}\Bigg|_{\text{Full scale}} \tag{46}$$

It is assumed that everything is known in this equation except the full-scale values of U and Δt. Thus, another equation is needed in order to solve for the two unknowns of the second equation. If the ratio of particle speed to wind speed is the same in model and full scale, then the second equation would be:

$$\left.\frac{U\Delta t}{L}\right|_{\text{Model}} = \left.\frac{U\Delta t}{L}\right|_{\text{Full scale}} \tag{47}$$

For the example Run No. 10-17-1, the values of full-scale wind speed U and time duration Δt would be 14.68 m/sec (32.8 mph) and 14 hr 6 min, respectively.

The ratio of particle to wind speed is not likely to be the same full-scale value as in the model, so it is probably more appropriate to search for an alternate second equation. This was done by equating the modified Richardson equations, i.e.:

$$\left.\frac{\rho}{\rho_p}\frac{U^2}{gh}\left(1-\frac{U_o}{U}\right)\right|_{\text{Model}} = \left.\frac{\rho}{\rho_p}\frac{U^2}{gh}\left(1-\frac{U_o}{U}\right)\right|_{\text{Full scale}} \tag{48}$$

Then, in order to satisfy Eq. (46),

$$\begin{aligned}&\left.\frac{\Delta A}{UL\Delta t}\left[A_1^2\,\frac{D_p}{h}\left(\frac{U}{U_o}\right)^2\right]^{3/7}\right|_{\text{Model}}\\&\quad=\left.\frac{\Delta A}{UL\Delta t}\left[A_1^2\,\frac{D_p}{h}\left(\frac{U}{U_o}\right)^2\right]^{3/7}\right|_{\text{Full scale}}\end{aligned} \tag{49}$$

Equation (48) and (49) result in full-scale values for Run No. 10-17-1 of 22.16 m/sec (49.6 mph) for wind speed and 5 hr 32 min for storm duration. If the fundamental similitude Eq. (46) is valid for all wind speeds, then either the wind speed - time set of values of 14.68 m/sec - 14 hr 6 min or 22.16 m/sec - 5 hr 32 min are appropriate, since both sets satisfy Eq. (46). There probably are at least subtle differences with changes in wind speed, however, and thus the latter set is probably more valid (based on the investigator's experience and intuition). The extrapolated full-scale values using Eq. (48) and (49) are listed for all model experiments in the Supplement.

In order to determine full-scale values of time in the preceding figures (Fig. 37, 41, 45-64), it is necessary to realize that the wind tunnel free-stream speed was used to calculate the plotted values of dimensionless time. For Model 1, the speed at bridge height is 0.9 U_∞. In terms of bridge height speed, the dimensionless time is thus $(0.9)^3 = 0.729$ times the plotted value.

5. RECOMMENDATIONS

A goal of this research effort was to determine the suitability of wind tunnel modeling for reproducing field observed snowdrifting characteristics. The results of these experiments, conducted in the wind tunnel, using scale models with simulated snow storms, have been shown to correlate well with actual field conditions.

Another goal of this research project was, based on the testing of various types and configurations of simulated vegetation, to determine the "best" planting design for minimizing snow deposition on the roadway. The following are recommended.

Recommendation 1

It is important that snow control plantings be extended in the area adjacent to the side road embankment, in the windward direction, some distance away from the normal freeway right-of-way. (Plantings placed near the windward end of the bridge may in fact cause an increase of snow deposition on the freeway pavement.) Figure 69 illustrates the leeward drift accumulation extending to the roadway due to the barrier.

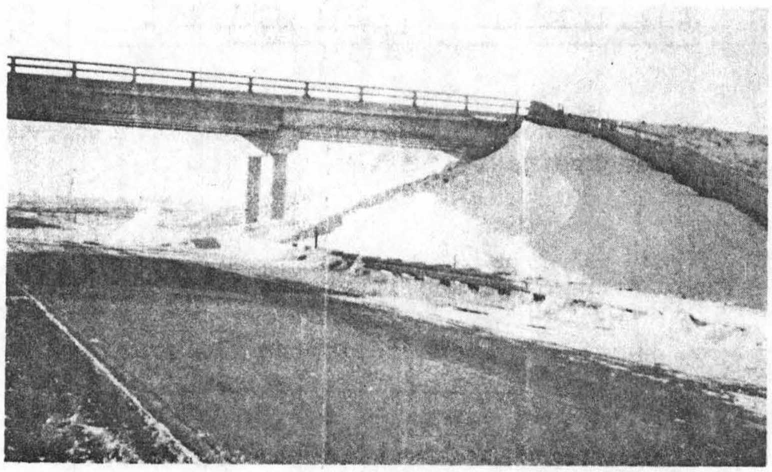


Fig. 69. Snowdrifting at grade separation structure.

Recommendation 2

The "best" planting arrangement to control snow deposition on the freeway pavement, where the right-of-way is constrained, is shown in Fig. 70. Note that this arrangement requires plantings on the minor road right-of-way.

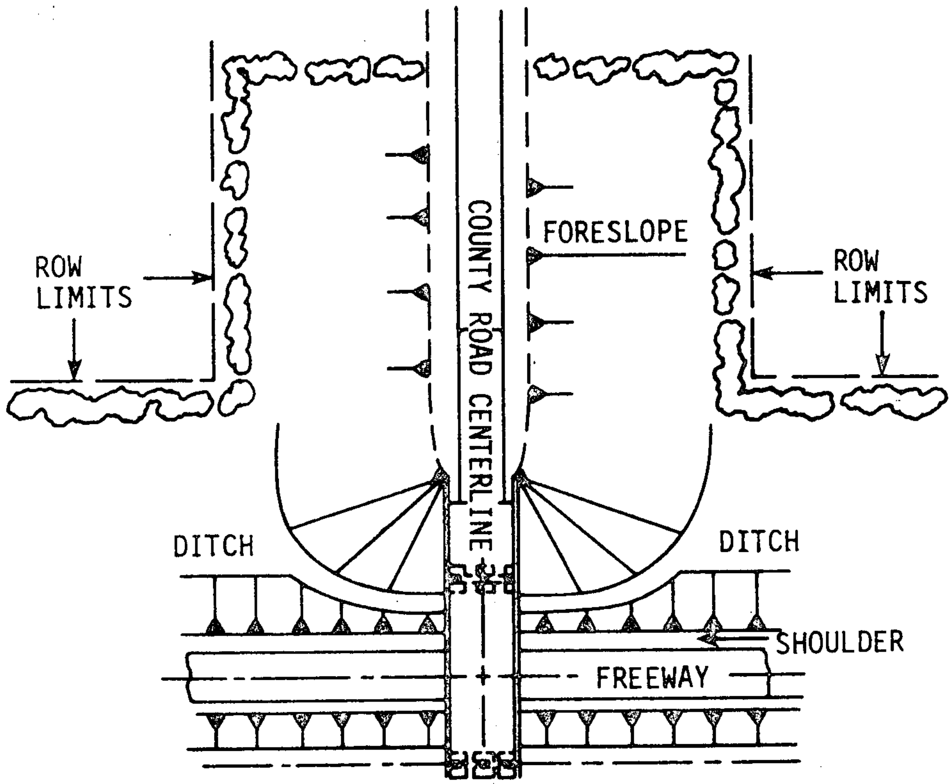


Fig. 70. Snowdrift control planting where right-of way is constrained.

The plantings, both along the interstate right-of-way and the minor road right-of-way, should have the following characteristics:

- Mature height should not exceed 10 ft
- Very low porosity at all levels within the plant mass

- Deciduous plants to induce drifting within the plant mass
- Adaptable to a variety of soil, drainage, and sun conditions.

Recommended plant selections for the constrained right-of-way condition are listed in Table 8.

Recommendation 3

The "best" planting arrangement to control snow deposition on the freeway, where the right-of-way is not constrained (such as at an interchange) is shown in Fig. 71. Acceptable alternate planting arrangements and dimensions for alternates may be obtained from details in this report and the Supplement.

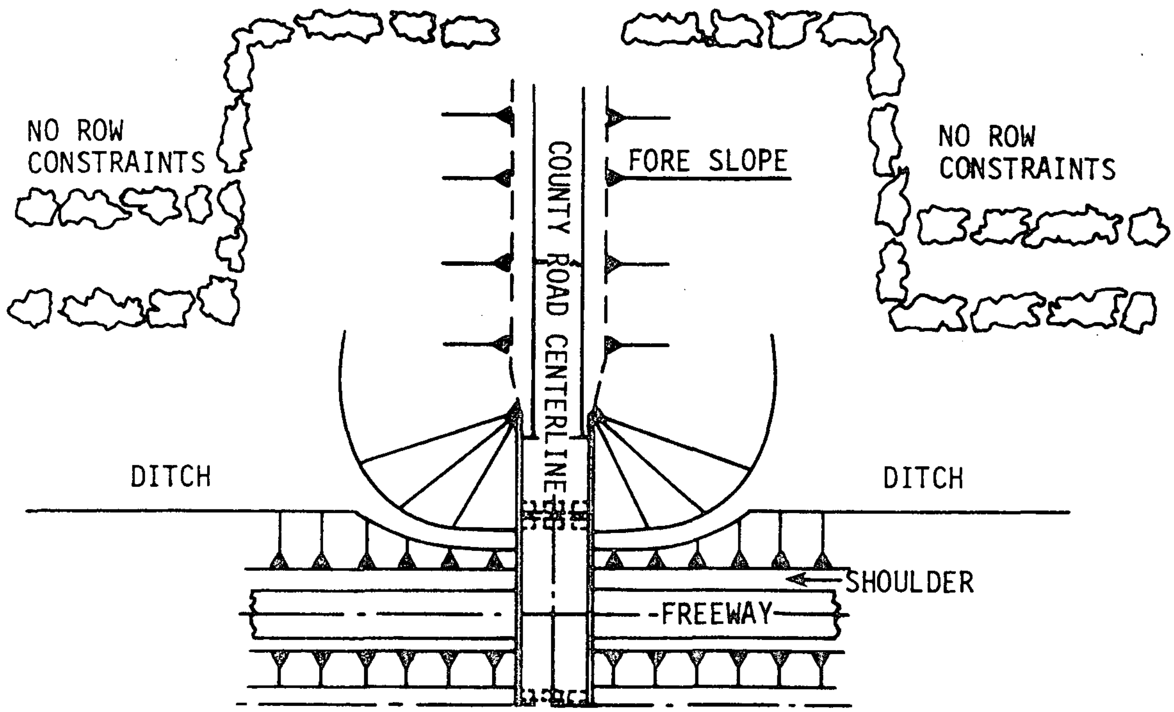


Fig. 71. Snowdrift control planting where right-of-way is not constrained.

Table 8. Recommended plantings for the constrained condition.[a]

Botanical Name	Common Name	Maximum Height at Maturity (Ft)	Number of Rows	Distance Between Rows (Ft)	Spacing in Rows (Ft)	Plant Mass Porosity	Special Considerations
Kolkwitzia amabilis	Beauty-bush	10	2	5	3	Low porosity at all levels	No special maintenance required.
Lonicera xylosteum "Claveyi"	Clavey's Honeysuckle	5	2	4	3	Very low porosity at all levels	No special maintenance required.
Lonicera Zabeli	Zabel Honeysuckle	10	2	5	3	Low porosity at all levels	No special maintenance required.
Syringa palibiniana	Dwarf Korean Lilac	6	2	4	3	Low porosity at all levels	May need to control lilac scale. May need pruning infrequently to maintain low porosity.
Ligustrum obtusifolium regelianum	Regel Border Privet	5	2	5	4	Very low porosity at all levels	No special maintenance required.
Ligustrum vulgare var.	Cheyenne Privet	10	2	5	3	Low porosity at all levels	No special maintenance required.
Physocarpus monogynus	Mountain Ninebark	4	2	3	2	Very low porosity at all levels	No special maintenance required; adaptable to most soils.
Rosa rugosa	Rugosa Rose	6	2	4	3	Low porosity at all levels	Tolerant to salt; no special maintenance required.
Rosa canina	Dog Rose	9	2	4	3	Low porosity at all levels	No special maintenance required.
Spiraea prunifolia	Bridalwreath Spirea	9	2	4	3	Low porosity at all levels	No special maintenance required.
Spiraea vanhouttei	Vanhoutte Spirea	6	2	4	3	Low porosity at all levels	Adaptable to wide variety of conditions; no special maintenance required.

[a]These lists are presented as a guide as to what types of plants have the characteristics needed to successfully carry out the best planting arrangements as they were modeled and tested. Satisfactory results may also be achieved by using different combinations of various plants on the list, such as, for example, two rows of two different varieties of shrubs, instead of two rows of the same variety.

The plantings used for the not constrained right-of-way situation (see Table 9) should meet the following criteria:

- Mature height may reach 20 ft if the entire plant mass has low porosity at all levels
- Mature height should not exceed 10 ft if the entire plant mass has medium porosity in the lower levels
- Multiple rows of plants should be used.

Recommendation 4

These recommendations are generalized for an idealized grade separation structure situation. Detailed variations in the actual "best" planting designs to control snow will depend on the topography, adjacent ground cover, nearby buildings, groves of trees, and other surrounding conditions at individual sites.

In order to evaluate these recommendations and the effect of such surrounding conditions a controlled field testing project should be initiated. A suitable length of north-south freeway should be designated for snowdrift research. The suggested "best" planting arrangements, with modifications based on specific site characteristics, should be carried out at both constrained and not constrained right-of-way locations. Adjacent similar sites could be established as controls, with no plantings provided.

These field test research sites should be monitored and an evaluation report prepared.

An important function of the field test proposal is to identify a number of "key" study sites as close to the idealized situation as

Table 9. Recommended plantings for the not constrained condition.[a]

Botanical Name	Common Name	Maximum Height at Maturity (Ft)	Number of Rows	Distance Between Rows (Ft)	Spacing in Rows (Ft)	Plant Mass Porosity	Special Considerations
Juniperus virginiana	Eastern Redcedar	20+	2	10	5	Very low porosity at all levels	Drought resistant. Adaptable to most soils. Need to mow surrounding area to prevent spreading. May need to top after 20 years.
Rhamnus frangula "columnaris"	Tallhedge Buckthorn	18	2	8	3	Low porosity at all levels	Disease resistant. Adaptable to most soils. No special maintenance required.
Caragana arborescens	Siberian peashrub	18	2	10	5	Low porosity at all levels	No special maintenance required.
Viburnum dentatum	Arrowwood	15	2	10	5	Low porosity at all levels	No special maintenance required. Adaptable to variety of conditions.
Crataegus phaenopyrum[b]	Washington Hawthorn	20	2	10	5	Low porosity at all levels	Adaptable to variety of soil and drainage conditions. No special maintenance required.
Acer ginnala[b]	Amur Maple	20	2	10	10	Medium porosity in the crown; low porosity in the lower level	May need to prune trees in later years to maintain medium porosity.
Elaeagnus angustifolius[b]	Russian Olive	20	2	10	10	Low porosity at all levels	Adaptable to most soils. No special maintenance required.
Viburnum lantana[b]	Wayfaring Tree	15	2	10	5	Medium porosity in the crown; low porosity in the lower level	Drought resistant. No special maintenance required.
Viburnum prunifolium[b]	Blackhaw	15	2	10	5	Medium porosity in the crown; low porosity in the lower level	Intolerant to flooding. Disease and drought resistant. No special maintenance required.

[a]These lists are presented as a guide as to what types of plants have the characteristics needed to successfully carry out the best planting arrangements as they were modeled and tested. Satisfactory results may also be achieved by using different combinations of various plants on the list, such as, for example, two rows of two different varieties of shrubs, instead of two rows of the same variety.

[b]These plants must be planted in combination with one windward row of any of the shorter (4-5 ft maximum height) deciduous shrubs listed in Table 8. The "Plant Mass Porosity" given here refers to the porosity of the entire plant mass.

possible. A flat landscape, no major standing crops in the adjacent area, no barriers such as trees, buildings, or other objects is desired. Also, a history of snowdrifting problems at these sites is necessary.

Another important function of the field test proposal is to demonstrate the importance of specific site characteristics upwind in designing the best and most efficient snowdrift control planting. A comparison should be made of the differences in maintenance needs due to snow on the road near a windbreak designed with specific site characteristics in mind and a windbreak based on an idealized situation with no attention paid to upwind characteristics.

Following the development of the recommended "best" planting configurations, as established from this model experimentation research program, an evaluation of the performance of these idealized "key" sites would be required.

Recommendation 5

The applicability of guard rail location should be examined at each site. Moving the guard rail away from the pavement edge significantly improves the snow free maintenance potential. Also, there are other types of guard rail in use by other states in the snow belt that have suitable minimum deflection, and that minimize snowdrifting from the guard rail installations. It is recommended that installations of this type be used and the results monitored.

Recommendation 6

To minimize drifting under and adjacent to bridges, in addition to the previously noted plantings, the shoulder area and the embankment area adjacent to the structure must be kept as aerodynamically smooth as possible. This requires removal of all possible obstructions such as existing shrubbery and clumps of material, and close mowing of the grass late in autumn.

Recommendation 7

A program for eventual implementation of an Iowa snowdrift control plan should be initiated. Every structure on Iowa's interstate system should be surveyed to determine its peculiarities in terms of upwind topography, vegetation, and other boundary layer obstructions (such as buildings). The planting arrangement at each site should be designed utilizing that information plus the knowledge gained from wind tunnel and full-scale site experiments.

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7. APPENDIX

7.1. List of State Highway Departments Surveyed

State Highway Departments Surveyed

1. Colorado
2. Idaho
3. Illinois
4. Indiana
5. Iowa
6. Kansas
7. Michigan
8. Minnesota
9. Missouri
10. Montana
11. Nebraska
12. North Dakota
13. Ohio
14. South Dakota
15. Wisconsin
16. Wyoming

7.2. Letter Requesting Participation

Gentlemen:

The Iowa DOT has contracted with the Engineering Research Institute at Iowa State University to conduct research into the phenomenon of snow drifting at grade separation structures on the freeway system. Under certain conditions of minimum snowfall, but with winds at a critical velocity and orientation, large deposits of snow have occurred on the freeway lanes under the structure. Scale models will be constructed and will be tested in the Iowa State University Aerospace Department wind tunnel to reproduce this snow drifting phenomenon. When the laboratory "modeling" duplicates the perceived field conditions the model will be modified to represent the intoduction of plantings and changes in the physical configuration of the adjacent topography. The effect on the snow drifting phenomenon will be observed, and recommendations for field testing will result.

In order to provide background information relative to the snow drifting phenomenon a literature search is underway. In addition this survey is investigating the normal design and maintenance "philosophies" (relative to snow drifting) associated with highway design and operation. The attached questionnaire will take only a few minutes to complete, and will contribute to a more meaningful research project.

Your help in providing this information will be appreciated.

Sincerely,

Stanley Ring, P.E.
Principal Investigator

SR/db
enclosure

7.3. Survey Instrument

A SURVEY OF

HIGHWAY DESIGN AND MAINTENANCE PRACTICES FOR MINIMIZING SNOW DRIFTING

Date____________________ Organization____________________________________

Person completing this instrument: Telephone #_______________

Name______________________________ Position______________________________

Does your organization have a policy, procedure, or guide regarding any of the following highway elements, with applications to minimize the drifting of snow on the traveled way? (If the policy, procedures, or guide is documented please include a copy.)

* *

1. Highway grade line design. Yes____ No____
   Comments:____.

2. Highway cross section design. Yes____ No____
   Comments:____.

3. Type and location of plantings. Yes____ No____
   Comments:____.

4. Overhead bridge structure design. Yes____ No____
   Comments:____.

5. Guard-rail, signs, and other appurtenances. Yes____ No____
   Comments:____.

6. Side road approach grade and cross section. Yes____ No____
   Comments:____.

7. Adjacent land areas. Yes____ No____
   Comments:____.

* *

Have you conducted any research on the snow drifting phenomenon? Yes____ No____. If answer is yes, please attach a list of references. (If references are not readily available, a copy would be appreciated.)

* *

Do your field maintenance personnel have any directives, policies, procedures, etc., regarding this particular phenomenon? Yes____ No____. If answer is yes, please include a copy of the item, or a statement if not documented in suitable transmittal form.

* *

Has your organization perceived a unique snow drifting problem at grade separation structures when the amount of snowfall is not causing problem drifting on the highway? Yes____ No____

Comments:____

____

____.

* *

A plan sheet of a typical grade separation at a freeway overcrossing in your state would aid our research analysis. A plan sheet is enclosed. Yes____ No____

* *

Has your organization developed a specific treatment (planting, snow fences, guard rail adjustments, topography changes, etc.) directed toward the reduction of snow drifting under grade separations at a freeway overcrossing? Yes____ No____

Comments:____

____

____.

7.4. Summary of the Survey of State Agencies

Summary of the Survey of State Agencies

September 1978

AGENCY	Grade Line Design	Cross Section Design	Plantings	Overhead Bridge Structures	Guard-rail, Signs, etc.	Side Road Approach	Adjacent Land Areas	Research	Field Maintenance Policies	Drifting At Grade Separation	Plan Sheet	Specific Treatment
Colorado	N	Y(C)	N	N	N	N	Y(C)	N	N	Y(C)	Y	N(C)
Idaho	N(C)	N(C)	N	N	N	N	N(C)	N	N	N(C)	Y	N(C)
Illinois	N(C)	Y(C)	Y(C)	N(C)	N(C)	N	Y(C)	N	Y(C)	Y(C)	Y	N(C)
Indiana	Y(C)	N	N	N	N	N	N	N	N	N	Y	N

Colorado Comments:

(2) Widen ditches and flatten slopes
(7) Use snow fences
(10) Problem encountered in eastern colorado on I70
(12) Tried placing snow fence on slopes of overpass grade, but have been unsuccessful

Idaho Comments:

(1) Designers have traditionally considered drifting snow in establishing grade lines
(2) Slopes are flattened when feasible in areas where drifting is a problem
(7) Sloping easements are sometimes obtained from adjacent owners and slopes flattened to minimize drifting
(10) Some drifting occurs at structures but the accumulation is small during light snowfall. Drifting in roadway cuts usually becomes a problem before drifting at structures
(2) Roadsides in areas subject to drifting snow are mowed in the late fall to minimize drifting

Illinois Comments:

(1) We recognize that an elevated grade line would help alleviate the problem in many cases. It should receive more attention
(2) Refer to attached (with original survey) standards 2235 and 2187. While the present design was not dictated by drifting considerations, the 3' ditch, flatter slopes and resultant wider R.O.W. do give more "storage" area and help with drifting problem
(3) Needs more consideration than received in past. See attached (with original survey) booklet recently prepared by Bur. of Maintenance Plantings can help or hurt depending on how used. We plan to pursue this further in the future
(4) Needed. The attached booklet addresses possible corrective action through use of selective landscape plantings
(5) We recognize that guardrail can cause drifting. We use the criterian in the 1977 AASHTO Guide for Selecting, Locating & Designing Traffic Barriers. We hope to minimize the use of guardrail where feasible
(7) Snow fence must usually be erected on adjacent land in order to obtain sufficient distance from the pavement. (See material on snow fence.) Need more attention to permanent plantings or other aids in adjacent land.
(9) See attached (with original survey) booklet. Also, information on use of snow fence
(10) It is a major problem. We feel your proposed research in this area is excellent and will be much interested in the results
(12) It is addressed in attached (with original survey) booklet entitled "Effects of Roadside Vegetation on Drifting Snow". We will be giving more attention to this and trying some different methods and procedures.
NOTE (included in original survey) pertaining to proposed legislation to allow Illinois DOT to make agreements with farmers of adjacent land and to pay them to leave standing row crops in the field to serve as snow fence

Indiana Comments:

(1) General policy of keeping grade above adjacent land where drifting is likely to occur and other conditions permit

AGENCY	Grade Line Design	Cross Section Design	Plantings	Overhead Bridge Structures	Guard-rail, Signs, etc.	Side Road Approach	Adjacent Land Areas	Research	Field Maintenance Policies	Drifting At Grade Separation	Plan Sheet	Specific Treatment
Iowa	Y(C)	Y(C)	Y(C)	N	N(C)	N	N	N	N	Y(C)	Y	Y(C)
Kansas	Y(C)	Y(C)	N(C)	Y(C)	Y	N(C)	N	N	N	Y(C)	Y	N(C)
Michigan	Y(C)	Y(C)	Y(C)	N	N	N	N	Y(C)	N	N	Y	N
Minnesota	N	N	Y(C)	N(C)	N(C)	N	N	Y(C)	N	Y(C)	Y	Y(C)
Missouri	Y(C)	N	N(C)	N	N	N	N	N	N	N(C)	Y	N

Iowa Comments:
(1) Nothing in writing, but grade generally kept 3-4 feet above surrounding terrain when possible
(2) Cross section set up more on safety emphasis, but flat slopes and wide cut sections minimize drifting ditches are capable of storing snow
(3) Living snow fence planted in areas of known snow problems. Doubles for wildlife cover
(5) Use of cable rail will minimize. Also placement of beam rail further from edge of travelway will help
(10) High winds during or following light to moderate snowfall deposit snow beneath underpasses when remainder of the roadway is generally clear. Temperature and snow density has considerable effect on this.
(12) Plantings have been used on berm slopes to reduce snow drifting under structures cannot always use because of available space.

Kansas Comments:
(1) See attached (with original survey) guide
(2) See attached (with original survey) guide
(3) Keep plantings back from roadway
(4) Keep spans open
(6) See #1 and #2
(10) On occasion we have observed this condition, however, in general the situations are isolated cases
(12) Some plantings have been made to produce a living snow fence

Michigan Comments:
(1) For years we have admonished designers to try for windswept grades in rural areas, consistant with other restraints
(2) Like #1 we try to design for snow storage. However, in recent years safety and environmental considerations have taken restraints
(3) We avoid plantings which will result in drifts on the roadway
(8) References included with original survey

Minnesota Comments:
(3) We shall install snow drift control plantings at the known trouble spots along state highways. Most plantings are located along and behind cut slopes at interchanges and along the R.O.W.
(4) Increased distance between shoulder and pier required for safety -- snow storage space is incidental additional benefit
(5) The use of three-cable guard rail is encouraged in lieu of plate beam to minimize drifting
(8) References included with original survey
(10) Maintenance forces report occasional need for rotary plows when other sections of road may be relatively free of snow problems
(12) See attached (with original survey) copy of snow control planting plan. (Additional comments on original survey.)

Missouri Comments:
(1) Grade line is designed slightly above adjacent ground where feasible and practical
(3) Not to any significant extent
(10) Not a significant problem. Some drifting is experienced with structures, guardrail and wind rows of plowed snow, but generally does not significantly affect roadway

AGENCY	Grade Line Design	Cross Section Design	Plantings	Overhead Bridge Structures	Guardrail, Signs, etc.	Side Road Approach	Adjacent Land Areas	Research	Field Maintenance Policies	Drifting At Grade Separation	Plan Sheet	Treatment
Montana	Y(C)	Y(C)	N	N(C)	N(C)	N	N	N	Y(C)	N	N	N
Nebraska	N	N	Y(C)	N	N(C)	N	N	N	N	Y(C)	Y	Y(C)
North Dakota	Y(C)	Y(C)	N	N	N(C)	N	Y(C)	N	N	N	Y	N
Ohio	N	N	N(C)	N	N	N	N	N	Y(C)	N(C)	Y	N
South Dakota	Y(C)	Y(C)	N(C)	Y(C)	Y(C)	N	N	N	N	Y	Y	N

Montana Comments:
(1) Try to keep the grade above surrounding terrain in areas with drifting problems
(2) Avoid sharp edges and use wide ditches and flat slopes
(4) We usually try to use conventional structures instead of big pipes for vehicular use in snow drifting areas because the pipes plug worse
(5) We try to minimize the use of guardrail because it does cause drifting
(9) See attached (with original survey) excerpt from our Maintenance Manual

Nebraska Comments:
(3) Enclosed (with original survey) plans showing plantings
(5) We do look at the feasibility of using cable guardrail
(10) Our interstate system is basically east-west with winter winds predominantly from the northwest which cause our drifting problems at grade speparations
(12) See plan as shown under=3

North Dakota Comments:
(1) Attempt to provide grade line 1.5' above terrain in flat areas
(2) Provide ditch bottom widening wherever possible, particularly on sides of prevailing winds. Normal inslope height of 4' provides snow storage in ditch
(5) Experiencing extreme difficulty with "w" beam guardrail in many locations. We are working on problem solution
(7) Maintenance sometimes obtains landowner's permission to "ridge" snow on private property which will act as natural snow fence

Ohio Comments:
(3) We have a few limited applications of living snow fence
(9) See note below and DH-20-DM enclose (with original survey)
(10) Drifting occurs but only when there is general drifting in the area

NOTE The amount of snow fence errected in recent years has decreased because of the following:
1. Changing farm practices (i.e. winter plowing) and residential development along highways
2. Reduced man power available for maintenance activities
3. To place snow fence or design to minimize drifting one must assume the storm will approach from the direction of the prevailing winds, unfortunately this is not always the case in severe storms
4. Snow depths in recent severe storms have exceeded the height of the snow fence rendering it ineffective
5. Questions have been raised concerning the cost of effectiveness of snow fence

South Dakota Comments:
(1) In flat areas where plowing snow is a problem the grade line is placed 1.5' to 2' above the surrounding ground
(2) Flat back slopes (5:1) are used in cuts where problems are anticipated, ditch widening is considered also
(3) We have discontinued plantings within the highway right of way
(4) We use two-span structures over divided highways when possible, the 30' clear distance to bents has helped the snow problem
(5) Cable guide rail is used at locations that will permit, i.e. clear distance behind the rail

AGENCY	Grade Line Design	Cross Section Design	Plantings	Overhead Bridge Structures	Guard-rail, Signs, etc.	Side Road Approach	Adjacent Land Areas	Research	Field Maintenance Policies	Drifting At Grade Separation	Plan Sheet	Specific Treatment
Wisconsin	N(C)	N	Y(C)	N	N	N	N	N	Y(C)	N(C)	Y	N(C)

Comments:
(1) We have no actual procedure or policy but do attempt to locate grade lines to minimize the effect of drifting snow where possible
(3) Plant 75' to 100' from roadway. Plant 2 to 3 rows of coniferous trees or deciduous small trees and/or shrubs depending on situation and location.
(9) See (with original survey) Policy 55-1 page 2, Drift Procedure 55-1 page 4, Drift Prevention guardrail
(10) We have noticed instances where drifting has been a problem at elevated crossings protected by guardrail and not on the remainder of the highway. Apparently due to proximity to pavement of the guardrail installations. This can be a serious problem when there is no active snowfall but recent snow is being moved by strong winds
(12) Maintenance has erected snow fence and/or planted shrubs at the toe of fill slopes adjacent to long open areas where experience has shown that snow can be blown up the fill slope in sufficient quantities to result in deposits in the roadway. Most freeway grade separations where the lesser road goes over have been planted for beautification purposes which helps break up the steady air flow needed to create drifting

AGENCY	Grade Line Design	Cross Section Design	Plantings	Overhead Bridge Structures	Guard-rail, Signs, etc.	Side Road Approach	Adjacent Land Areas	Research	Field Maintenance Policies	Drifting At Grade Separation	Plan Sheet	Specific Treatment
Wyoming	Y(C)	Y(C)	N	N	N(C)	Y(C)	Y(C)	Y(C)	Y(C)	Y(C)	N	N(C)

Comments:
(1) See #2
(2) We have a snow drift prediction system that predicts drifts on x-sections. Adjusting grade line or slope modifies output
(5) We have modeled guardrail (see letter with original survey)
(6) In conjunction with snow drift Prediction Program
(7) In conjunction with snow drift Prediction Program
(8) References included with original survey
(9) See section 12-7 in Procedures Manual (with original survey)
(10) Grade separations have caused a problem on roadways without a normal drifting problem
(12) The snow fence was not developed specifically for grade separation protection but works effectively as such

7.5. Sample from Wyoming's Procedure Manual on Snow Control

SNOW CONTROL (12-7)

CURRENTLY BEING UPDATED TO ADD NEW RESEARCH DATA

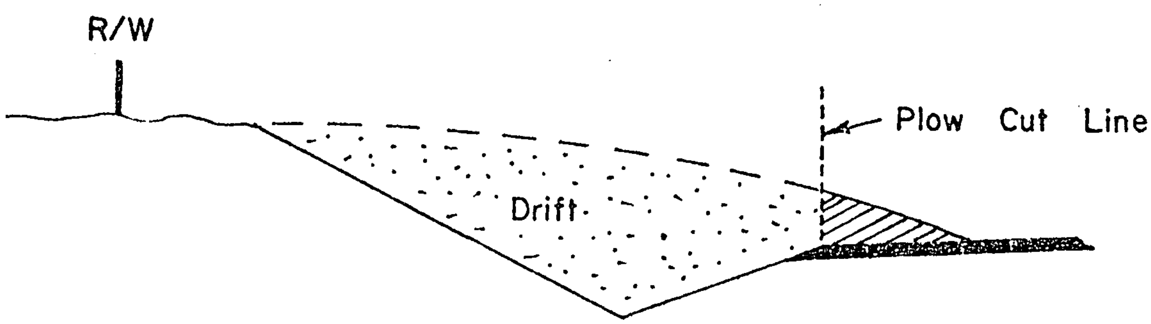
12-7.10 GENERAL

The drifting of snow in certain areas of Wyoming causes serious drifting and maintenance problems. These problems can be reduced considerably by proper highway design and efficient use of snow fence. Proper geometric design reduces the occurance of drifts forming on the traveled way.

There are two important factors to consider when designing for snow control; drifting snow and visibility. Drifting will continue throughout most of the winter whenever winds are present. The greater part of the drifting problem can be handled by proper geometric design, thus cutting maintenance costs of snow removal. In areas where proper design is not an economical solution, snow fence can be put to efficient use for drift control.

Visibility is the other factor to be considered. Poor visibility usually occurs during the intense part of the storm or during high wind conditions. Visibility conditions can be greatly improved by proper use of snow fence. With these two problems in mind, proper combination of snow fencing and geometric design should make most roads passable under winter conditions.

A typical drift on the highway is shown in the figure below. The drift tails out onto the traveled section of the roadway and requires plowing by maintenance personnel. Continuous plowing by maintenance forces temporarily alleviates the drift, but redrifting soon occurs. The plow as it passes through the drift leaves a vertical cut line. This plowed area quickly fills back in and the same problem exists all over again. If the drift is not plowed out immediately, dangerous traffic conditions exist. Better geometric design would cause the drift to form off the traveled way of which no plowing would be necessary. Elimination of this type of drift will greatly increase the safety of the highway and in turn cut maintenance costs. It may prove advantageous to spend extra money in the design and construction stage rather than expenditures for yearly maintenance.



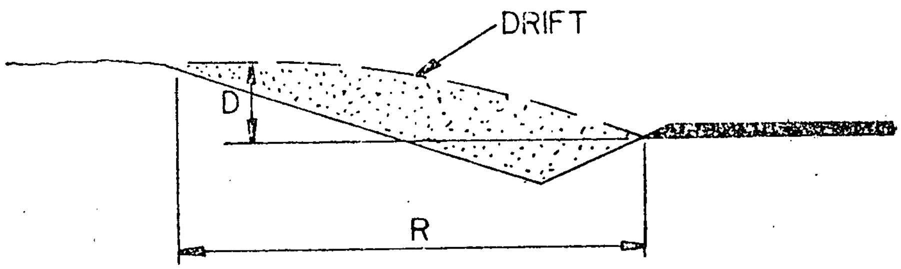
12-7.11 GEOMETRIC DESIGN

The following recommendations that will influence the roadway geometry apply primarily to those areas where blowing and drifting snow is a major maintenance problem. During the engineering inspection it can be determined if the roadway should be designed for adverse snow conditions.

a) Cuts

Understandably, the flatter the cut slope, the more efficient the cleaning action by the wind due to the streamlining effect. The following figure shows the minimum recommended width to depth ratio, that if adhered to, will keep the traveled way free from drifts. It is noted that this is the minimum criteria for design, therefore a designer should exceed this ratio whenever feasible to insure drift free shoulders. The average cut will be kept clean if the cut slope is a 6:1 or flatter. Cuts parallel to the prevailing wind will not require protection, while cuts perpendicular to the prevailing wind will require special treatment.

D	R
Cuts < 8'	12D
Cuts > 8'	6.5D



Cut slopes can be used to store snow, however caution is advised. The recommended width to depth ratio as noted above should be adhered to for maintaining a drift free roadway. If drifting is a problem then snow storage in the cut is of little use, when simply the geometry can be improved to eliminate the drift from the traveled way.

Deep cuts usually present the major drifting problems and also present the greatest expense for snow removal. Economy of right-of-way and disposal of material governs as to how flat the cut slopes may be. Snow fence can also be used to protect the cut, therefore, an economic comparison can justify the use of snow fence or the flattening of cut slopes. Snow fence will require maintenance and has a predicted life span while flat, glassy slopes will be aesthetically pleasing to the public and relatively maintenance free.

b) Fills

Cuts, by far, cause the most serious drifting problems. However, on fills with steep side slopes, an eddy area is created above the traveled way, thereby causing drifts to form. Continuous plowing by maintenance is required to keep the roadway free from drifts.

12-7.11 GEOMETRIC DESIGN (Continued)

W-Beam guard rail is also found on high, steep fills for protection of motorists, but it is a potential drift former by acting as a minature snow fence. Model studies on fills show that a slope of 4:1 or flatter will not create a drift on top of the road. Elimination of both steep side slopes and guard rail can effectively reduce drifting on fills. Flatter fill slopes enhance the safety features of the roadway and will cut maintenance costs for snow removal.

With some knowledge of prevailing winds and drifting problems in a given area, a designer has the opportunity to modify the geometry in the preliminary earthwork phase to eliminate potential drifts. This added expense may prove to be economical over a period of time where maintenance is concerned. The following slope selection table is recommended for those fills in bad snow areas that are viewed to be a potential drift former.

Slope	Fill Height
6:1	0-16'
4:1	Max.

12-7.12 ESTIMATING RELOCATED SNOW

If the geometry cannot be enhanced to eliminate drifting or if visibility becomes a problem, snow fencing should be employed. To properly design a snow fence system, one must approximate the amount of relocated snow arriving at the site. The amount of relocated snow (q) per unit width that must be stored at a given site is estimated by the following equation:[1]

$$q=\frac{1}{2}\theta PR_C - q_L - q_S$$

P is the average precipitation received over a given winter year in feet.

R_C is the contributing distance of the relocated snow. Studies conducted on the Laramie-Walcott Junction Project found this value to be 4500 feet.

θ is the ratio of the amount of relocated snow verses that which falls as precipitation and is usually taken as one.

q_L is the snow loss due to sublimation.

q_S is the amount of natural storage over the contributing distance given in ft. ^{3}/ft. In most cases this can be assumed as zero unless a major storage site exists.

The above equation can be simplified to:

$$q = 2250P - q_S$$

1. Ronald Tabler, ABSTRACT, New Engineering Criteria for Snow Fence Systems, 1973.

The precipitation design value is established from an average winter year. The winter year is usually 4 to 6 months long depending upon the area in question. Other months can have snow precipitation, but it is assumed that this moisture will melt or evaporate away. The NOAA (National Oceanic and Atmospheric Administration) provides monthly precipitation data and also 20 year monthly mean precipitation data, which is useful in estimating the average design precipitation.

Difference in elevation and large topographic projections have a significant effect on the amount of snow fall received in a given area. Caution is advised when adjusting data from a field gaging station to the area in question.

12-7.13 SNOW FENCE STORAGE

The estimated amount of snow stored behind a snow fence is a function of the fence height and topography of the surrounding area. The estimated Water Equivalent capacity of a given height snow fence on level terrain is determined by the equation below.[2] On a uniform slope of less than 10% either upward or downward, a fence will store snow equivalent to level terrain.

$$W_s = 7.35H^{2.09}$$

W_s is the Water Equivalent Capacity of the fence in the $ft.^3/ft.$

H is the nominal vertical height of the fence in ft.

SNOW FENCE STORAGE CAPACITY
(level terrain)

Nominal Fence Height	8'	10'	12'
Water Equivalent	560	900	1320

Terrain characteristics 150' in front of and 300' behind the snow fence play an important role in influencing drift patterns. In locating the snow fence a designer should be aware of and put to efficient use the surrounding terrain features. The ideal installation for optimizing drift storage is an upslope condition to the snow fence and a downslope behind fence.

12-7.14 EXAMPLE

Given: The contributing precipitation is taken from the winter year November 1 - March 31. NOAA total average precipitation for these months is 5 inches.

[2] Tabler

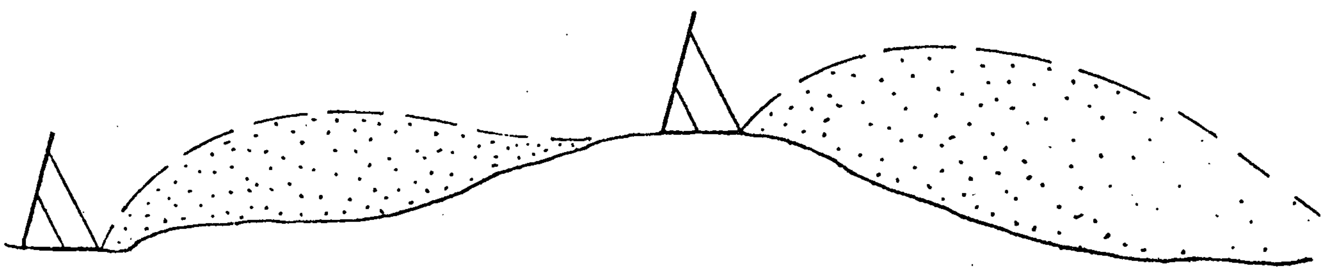
12-7.14 EXAMPLE (Continued)

Solution: $q = 2250' \times \frac{5''}{12} - \cancel{q_s}^{0} = 938 \text{ ft.}^3/\text{ft.}$

Design: Use one row of 10' snow fence yielding 900 ft. ^{3}/ft. total storage capacity at each control site on level terrain.

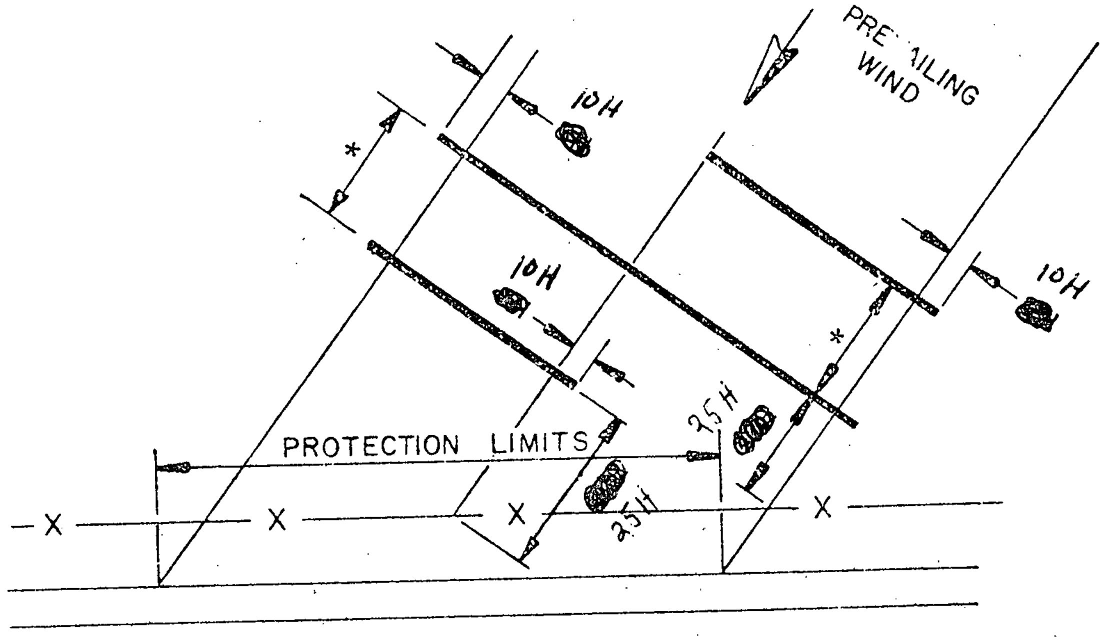
12-7.15 PLACEMENT OF SNOW FENCE

Proper placement of snow fence is essential lest one creates a problem worse than the original one. Snow fences located too close together or at the top of a cut are typical misplacements. A spacing of 30 H is desirable to prevent placing the snow fence too close to the road or fence line and thus creating a further maintenance problem. The snow fence should be located on the crests of hills or ridges if possible thereby optimizing the drift.



Proper orientation of the snow fence is also essential as a fence skewed to the prevailing wind will lose it's effectiveness. Direction of the prevailing wind at each control site is very critical as the wind can deflect around hills, woods, etc. The fence should be placed at right angles to the prevailing wind if possible.

The snow fence should not be placed in short, choppy sections. Each end of a line of snow fence has a drift loss due to an "end washout effect". Therefore, the snow fence should be in runs as long as possible to minimize this effect. The snow fence should overlap the established protection limits by 8H to accommodate for the end losses. The following figure shows the proper placement of the snow fence at a control site.



SPACING TABLE

Slope	Spacing
>10% up slope	25H
level	30H
>10% down slope	35H

* See Table

12-7.16 PREVAILING WINDS

One of the most important design criteria necessary for proper snow fence orientation is the prevailing wind direction. The field wind measurements should be taken in the winter months and as frequently as possible to insure an average wind direction. Aerial photography immediately after major winter storms is a very valuable tool in studying wind patterns and significant drift areas. The photographs prove to be invaluable for proper placement and orientation of the snow fence in relation to topography and wind direction. Prevailing wind angles should be determined at the proposed snow fence site rather than at the roadway. For example, the wind turbelence area created in the cuts may cause wind patterns different than those actually existing at the proposed fence site.